Lecture - 1
ENGINEERING DESIGN: ANALYSIS, MODELING, AND OPTIMIZATION

Reference: Book Chapters 3 and 4

MOTIVATION FOR OPTIMIZATION

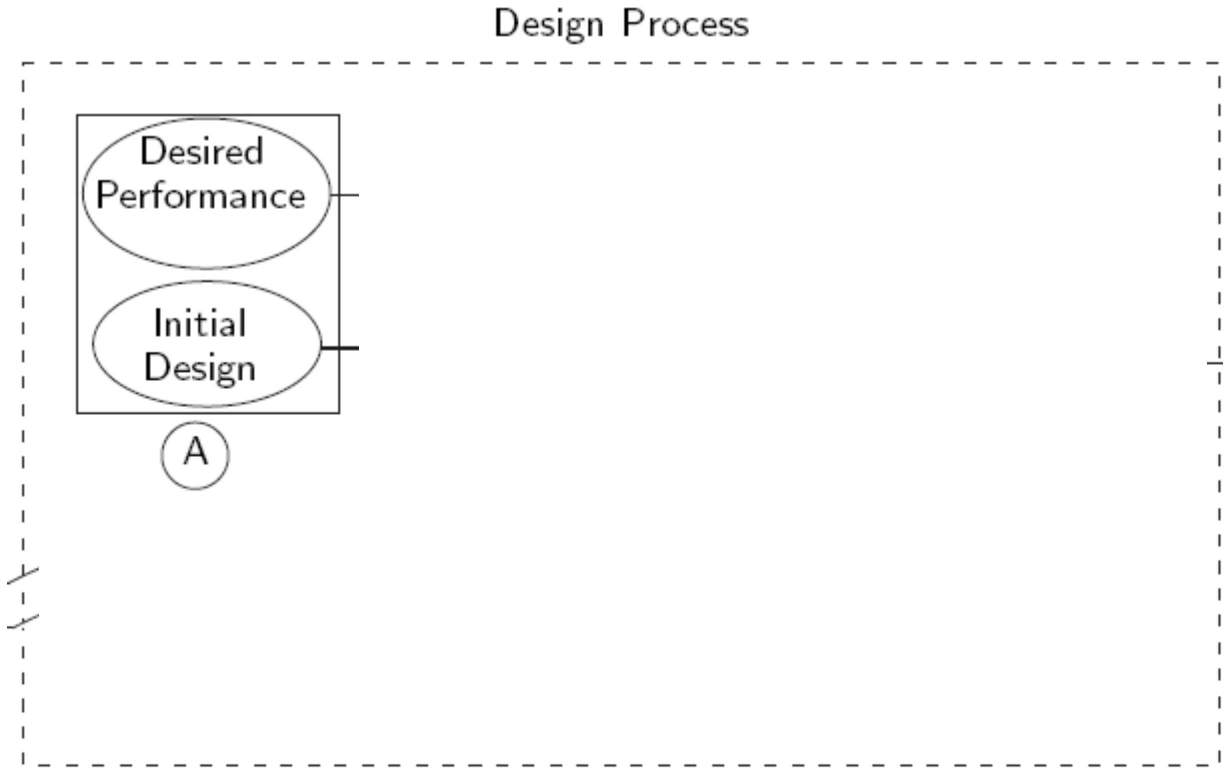
"I'VE GOT TOO MUCH WORK TO DO TO STOP AND LISTEN TO YOU"

WHAT IS OPTIMIZATION?

- In practice, doing something as well as possible within practical constraints is very satisfactory.
- Optimization provides us with the means to make things happen/ work in the best possible practical way.
- Brute-force or manual optimization is done by trial and error, and using past experience, which for most practical problems:
  - Will lead to highly sub-optimal solutions, since only few trials can be performed in a limited time, and/or
  - Is too time consuming to be practically feasible.
- This is where **quantitative optimization** comes in:
  - Uses mathematical strategies to provide an efficient and systematic way to optimize.
  - Using the capabilities of modern day computing, these mathematical strategies become all the more powerful in implementation.

TRADITIONAL VS. MATHEMATICAL OPTIMIZATION PROCESS

- Box A shows two inputs – 1. the dream design and 2. the initial design.
- Box B shows the analysis phase.
- Box D is where the design is improved in a very systematic way.
- Box E shows manual optimization by a human being (trial & error/intuitive)



TRADITIONAL VS. MATHEMATICAL OPTIMIZATION

Might take forever without reaching desired performance

Not an organized approach

Traditional Non-Opt:
Do trial and error.

Point A
(Initial bad design)

Point B
(Great optimal design)

Optimization

Yield optimal designs in a reasonable timeframe

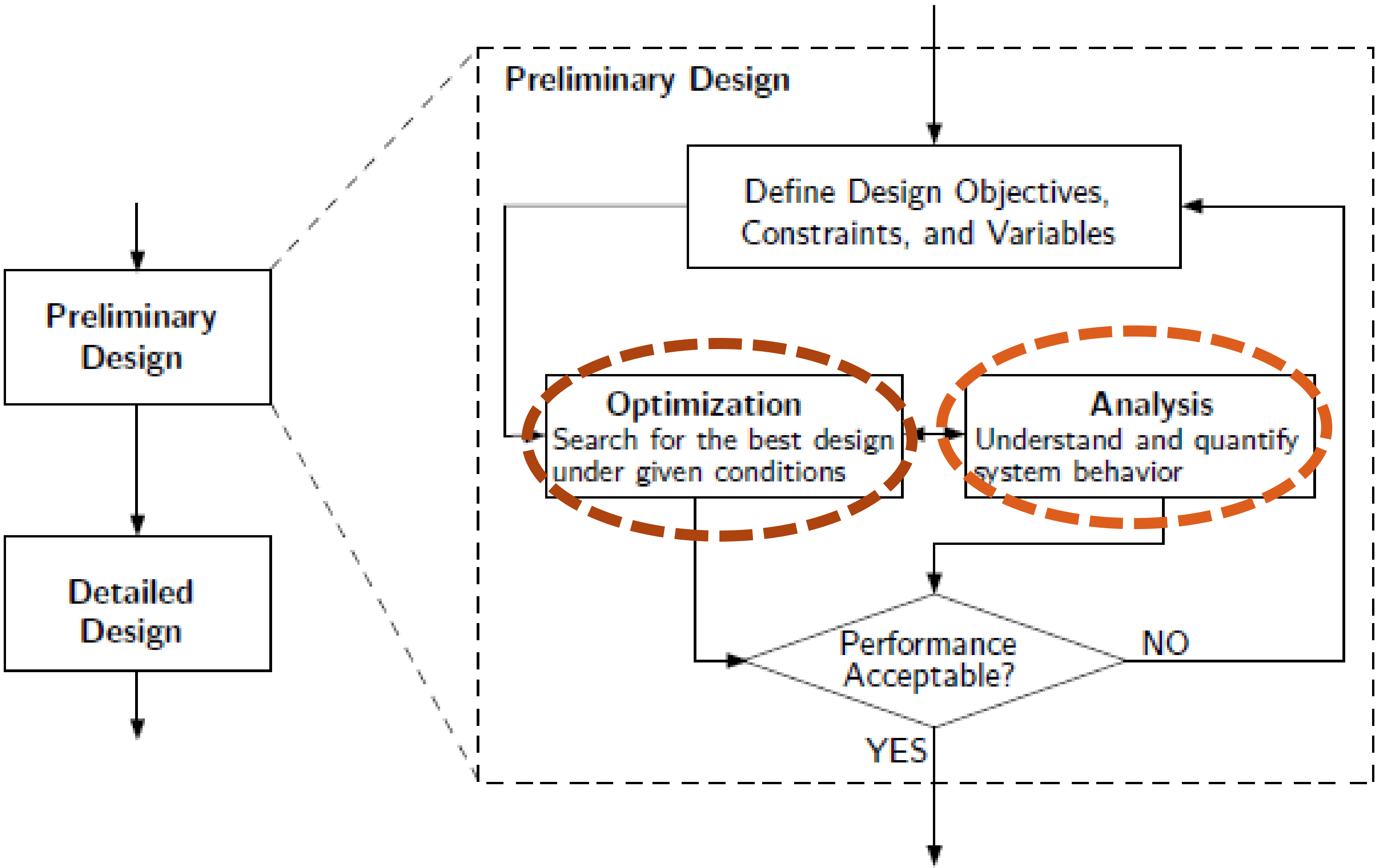
A systematic approach

WHY SHOULD WE STUDY OPTIMIZATION?

- **Undergraduates**: To acquire the ability to optimize designs yourself, and feel comfortable and confident with the results
  - As a student, in the classroom setting (e.g., Capstone Design project);
  - As an engineer (post graduation), in the industry setting.
- **Graduate Students**: To be able to use optimization to find better ways to proceed with your experiments, system modeling, or designs, in the course of your ongoing and future research.
- **Industry Personnel**: To acquire the ability to leverage the immense potential of optimization in different real-life projects.
  - Learn software tools to readily apply optimization in your projects;
  - Acquire knowledge to be able to critically verify the optimal designs
  - Acquire knowledge to be able to identify the challenges in optimizing a system, and to know where to look for the solutions.

IMPORTANT COMPONENTS OF SYSTEMS DESIGN

- ***Analysis*** and ***Optimization*** are two core components of a systems design process.



WHAT IS ANALYSIS?

- Engineering Analysis can be defined as:

The application of scientific principles and processes to reveal the properties and the state of a system, and also understand the underlying physics driving the system behavior.

- Analysis generally demands disciplinary knowledge pertinent to the system or mechanism being analyzed.
- Practical systems involve multiple disciplines, e.g., designing an aircraft requires structural, aerodynamic, and control analyses.
- If disciplinary understanding has reached certain level of maturity, mathematical analysis tools might be readily available.
- On the other hand, in the case of mechanisms or phenomena that are not yet well understood, in-depth and fundamental analysis might be required thereby demanding the involvement of a disciplinary expert.

APPROACHES TO ANALYSIS

- Analysis need not be a purely mathematical or theoretical process, especially in designing new systems.
- Analysis could involve "experiments–testing–mathematical inference" as an iterative process.
- Such an approach is necessary due to any of the following reasons:
  1. The underlying physics is not well understood; the fundamental disciplinary principles or theory do not directly apply;
  2. There are geometrical complexities and inherent uncertainties; or
  3. There is a lack of knowledge of the material properties (e.g., thermodynamic or structural properties).

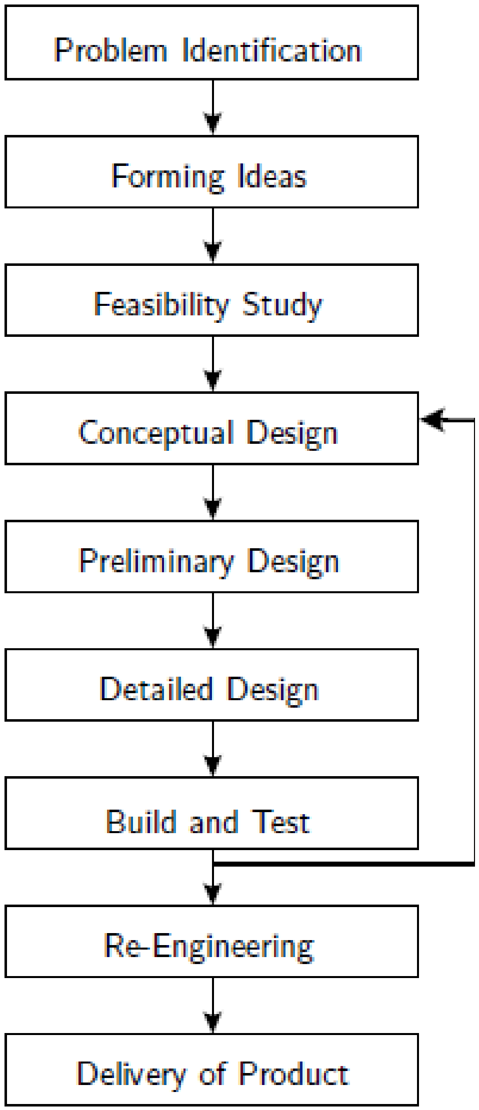
ENGINEERING DESIGN

- Design in general terms can be defined as *the creation of a plan and/or strategy for constructing a physical system or process.*

- Based on the "*object of design*", engineering design could be classified into:
  1. **product design**
  2. **systems design**
  3. **industrial design, and**
  4. **process design**

ENGINEERING DESIGN: PROCESS

- Practical engineering design can be perceived as a multi-stage process.
- Overlap or iteration among the different stages is often prevalent and necessary.



OPTIMIZATION

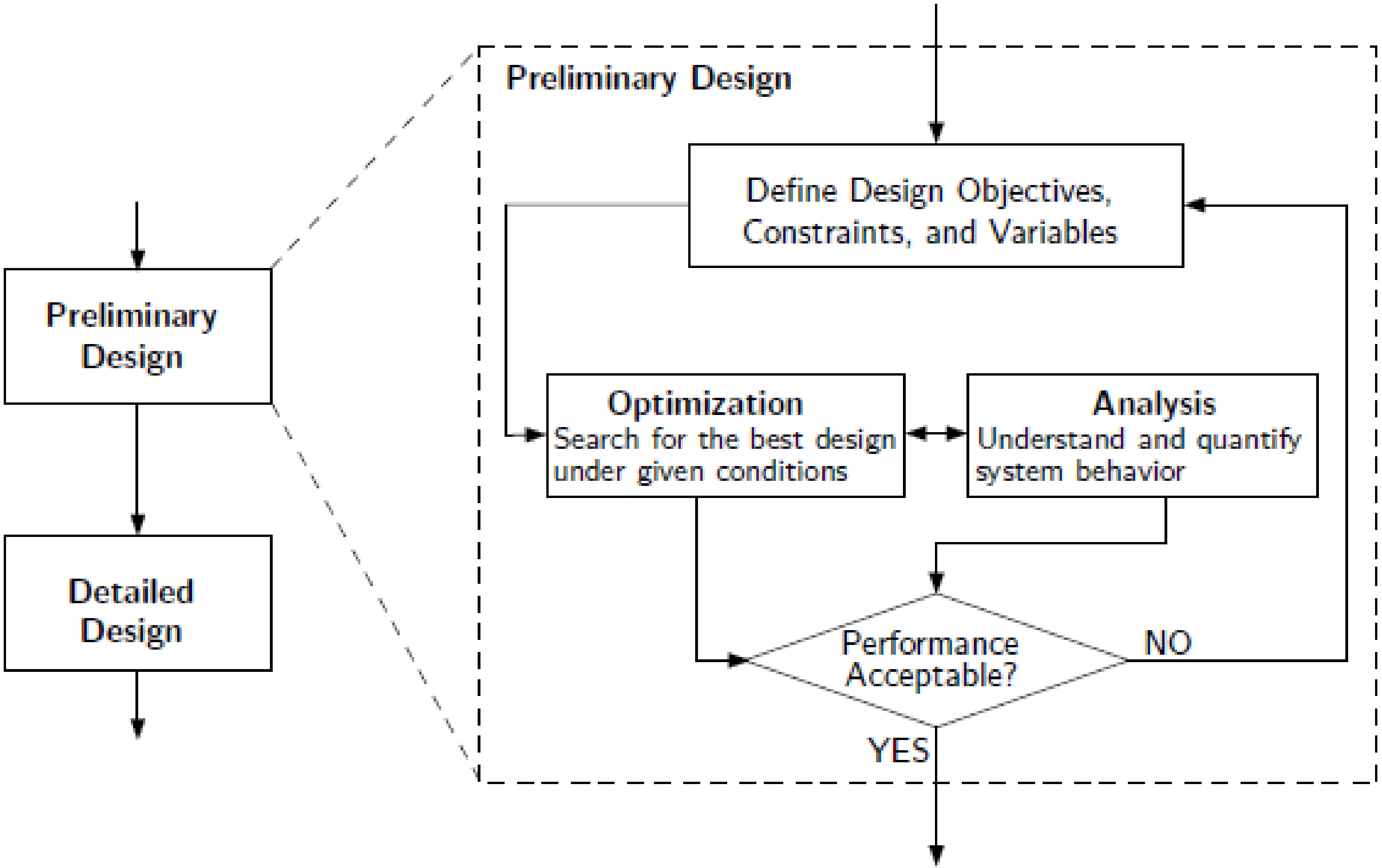
- ***Mathematical optimization is the process of <u>maximizing and/or minimizing</u> one or more <u>objectives</u> without violating specified <u>design constraints,</u> by regulating a set of <u>variable parameters</u> that influence the objectives and the design constraints.***

- The three types of quantities in optimization:
  1. **<u>Objectives</u>**: The quantities that you would like to improve – *e.g., fuel efficiency of an aircraft (to be maximized), or manufacturing cost of the aircraft (to be minimized)*.
  2. **<u>Constraints</u>**: The quantities or criteria that your design needs to satisfy – *e.g., the cargo/payload capacity of an aircraft*.
  3. **<u>Variables</u>**: The quantities that you can directly change to improve the design, where the values of the objectives and constraints are regulated by these quantities – *e.g., the dimensions and the material of the aircraft wing*.

Objective functions *and* ***constraint functions*** *are often together called* ***<u>criteria functions,</u>*** *since one can be converted into another.*

REVISITING DESIGN-ANALYSIS-OPTIMIZATION

- There does not exist a unique structure to how they are related – the structure generally depends on the available human, computational, and physical resources and on the choices of decision-makers.



DESIGN-ANALYSIS-OPTIMIZATION RELATION

- **Design** in general is the enveloping process that includes ***analysis*** and ***optimization*** as sub-processes.
- Primary steps in **design** include (i) defining the design objectives, constraints, and variables, (ii) performing or using analysis, and (iii) performing optimization, (iv) verifying the optimum design.
- **Analysis** provides you with the knowledge to relate the variable values to the criteria functions of interest (through models).
- **Optimization**, which is the main driver for improving the design, uses the knowledge (model) obtained through analyses.
- **Analysis** also provides the opportunity to investigate the performance of the final optimum design.
- On the other hand, **optimization** could provide food for further analysis – e.g., which region of the design space is to be analyzed in more detail.

OTHER COMPONENTS OF PRACTICAL DESIGN

- Engineering design could involve qualitative elements that go beyond quantitative "**analysis**" and "**optimization**", while often impacting these two quantitative activities.
- **Creativity- and aesthetics-driven decisions**: Although qualitative in nature, these decisions have important quantitative implications for the later stages of design where analysis and optimization are involved (*e.g., impact on material options*).
- **Market-driven decisions**: Design specification can also be driven by an understanding of the market, especially in the case industrial and product design. Although, quantitative market analysis might be available in certain cases, such availability is not necessarily generic (*e.g., imagine the first Iphone*).

MODELING FOR ANALYSIS

- In the context of design, analysis and optimization are related to each other through **modeling**.
- **Modeling**: *A process by which an engineer or a scientist translates the actual physical system/phenomena under study into a set of mathematical equations or operations*.
- Mathematically, modeling can be represented as: $\boldsymbol{P = f(X)}$, where, ***P*** the quantity of interest, which is expressed as a function of a vector of design variables, ***X***.
- Mathematical models may not be a single analytical function.

TYPES OF MODELS

- **Physics-based Analytical Models:** These are theoretical models derived from the physics of the system (e.g., analytical solution of the conduction heat transfer differential equation).
  - Generally fast in execution.
  - Often inadequate for complex systems (e.g., involving complex geometry).
- **Simulation-based Models:** These models generally leverage a discretized representation of the system, in translating the system behavior into a set of algebraic equations. These set of equations are solved using numerical techniques, by harnessing the power of computers. Examples include CFD.
  - Often time-intensive (could take hours/weeks/months).
  - Generally adequate in representing system complexities.
- **Surrogate Models:** Surrogate models are purely mathematical or statistical models, with certain generic functional forms and coefficients that can be tuned using a set of input-output data that is generated from physical or simulation-based experiments.
  - Fast in execution.
  - Can represent complex systems, generally at the cost of accuracy or fidelity.

MODELING THE OPTIMIZATION PROBLEM

- The success of optimization depends both on:
  - the capabilities of the optimization method/algorithm;
  - the effectiveness of the **optimization formulation**.
- Modeling the optimization or **problem formulation** essentially involves developing a clear definition of the design variables, design objectives, and design constraints.
- Problem formulation is also strongly correlated with the choice of optimization algorithms – e.g.

  During problem formulation, One can convert equality constraints into inequality constraints using a tolerance value, in order to leverage powerful algorithms that perform well in the absence of equality constraints.

MODELING FOR ANALYSIS AND OPTIMIZATION

- It is important to ensure that **optimization problem formulation** is coherent with the **system behavior model**.
- For example, the input output exchange (between analysis and optimization) demanded by the optimization formulation should be satisfied by the capabilities of the models used thereof.
- The choice of analysis models also affects the choice of optimization algorithm, and vice versa. For example:
  - If you choose an algorithm that generally requires a large number of system evaluations, then a fast model of the system behavior is needed.
  - If the system behavior model is inherently highly nonlinear, you will need to formulate the optimization problem such that a nonlinear optimization algorithm can be used to solve the problem.