Lecture 2

An Approach to MEMS Design

- Design: The Big Picture
  - Device Categories
  - High-Level Design Issues
  - The Design Process
- Modeling Levels
  - Analytical or Numerical?
  - A Closer Look
- Example: A Position-Control System

Design: The Big Picture

Microsystem Design

- As a first step, we examine the big picture, including difficult subjects such as creativity and invention, market opportunities, and choices of technologies, system architectures and manufacturing methods.
- Modeling plays a critical role in analyzing the choices that must be made.

Three Major Device Categories

- **Technology Demonstrations**

  - To drive development activity

  - To test a device concept

  - To push the capabilities and limits of a particular fabrication technology.

  - Small numbers of working devices are needed.

- **Research Tools**

  - Enabling research or performing a highly specialized task.

  - Such as measuring the value of selected material properties.

- **Commercial Products**

  - For commercial manufacture and sale.

Device Categories

- **Technology Demonstrations:** a handful of working devices.
- Device-to-device consistency is not usually of primary importance.
- **Commercial Products:** millions of devices per year.
- Device-to-device consistency and high manufacturing yield are important.
- **Research Tools** intend, for example, to perform a measurement of a quantity of interest.
- Calibration, repeatable behavior, device to device and measurement to measurement.
- **Technology Demonstrations => Research Tool => Commercial Product**.
- By categorizing microsystems this way, we can gain important insights into the design process

Five High-Level Design Issues

- **Market:** Is there a need for this product? How large is the market? How fast will it develop?
- **Impact:** Does this product represent a paradigm shift? Is it a new way of accomplishing something? Does it enable a new kind of system?
- **Competition:** Are there other ways to make an equivalent product? Are there other organizations building a similar product?
- **Technology:** Is the technology to make and package the product available? Is it in-house? Or must it be acquired through vendors?
- **Manufacturing:** Can the product be manufactured at an acceptable cost in the volumes required?

Relative Importance of High-Level Design Issues

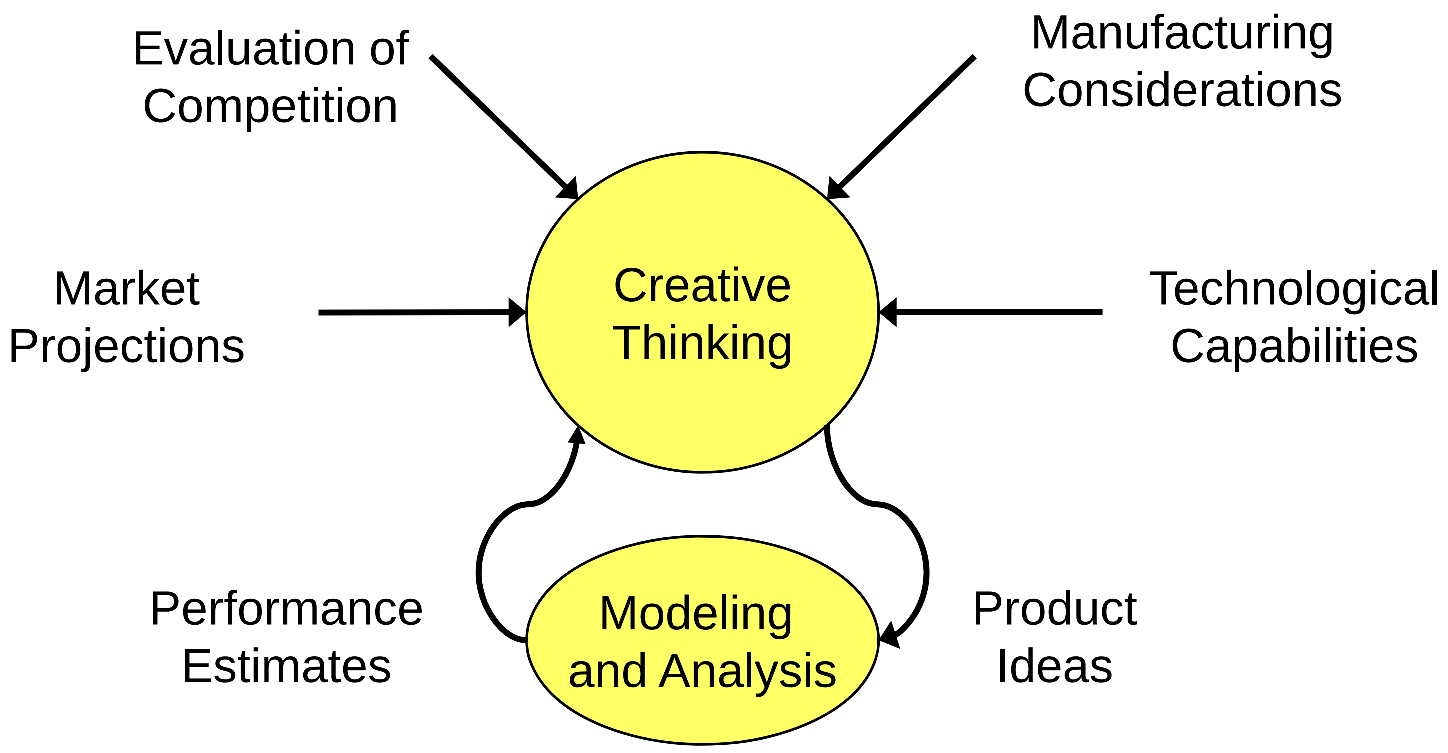
Category	Markets	Impact	Competition	Technology	Manufacturing
Technology Demonstration		++		+++	
Research Tools	++	++	+	+++	++
Commercial Products	+++	+++	+++	+++	+++

- Everything is critical for Commercial Products.
- Depending on end use, there is a moderate need to attend to all issues for the Research Tools.
- For example, device-to-device repeatability is required for Research Tools, and that begins to sound like a manufacturing issue.

The Design Process

- **Market-driven design:**
- The need for a specific capability is well understood.
- A search is made for device concepts and corresponding fabrication methods that can realize the desired capability at an acceptable cost.
- **Technology-driven design :**
- A specific set of technological capabilities have been developed.
- A search is made for device concepts and markets that can use this technology.
- **“Opportunistic” design:**
- Match a market opportunity with a new technology, achieving a paradigm-shifting way of meeting that market need, and doing so cost-effectively.

Implementation of Creative Thinking

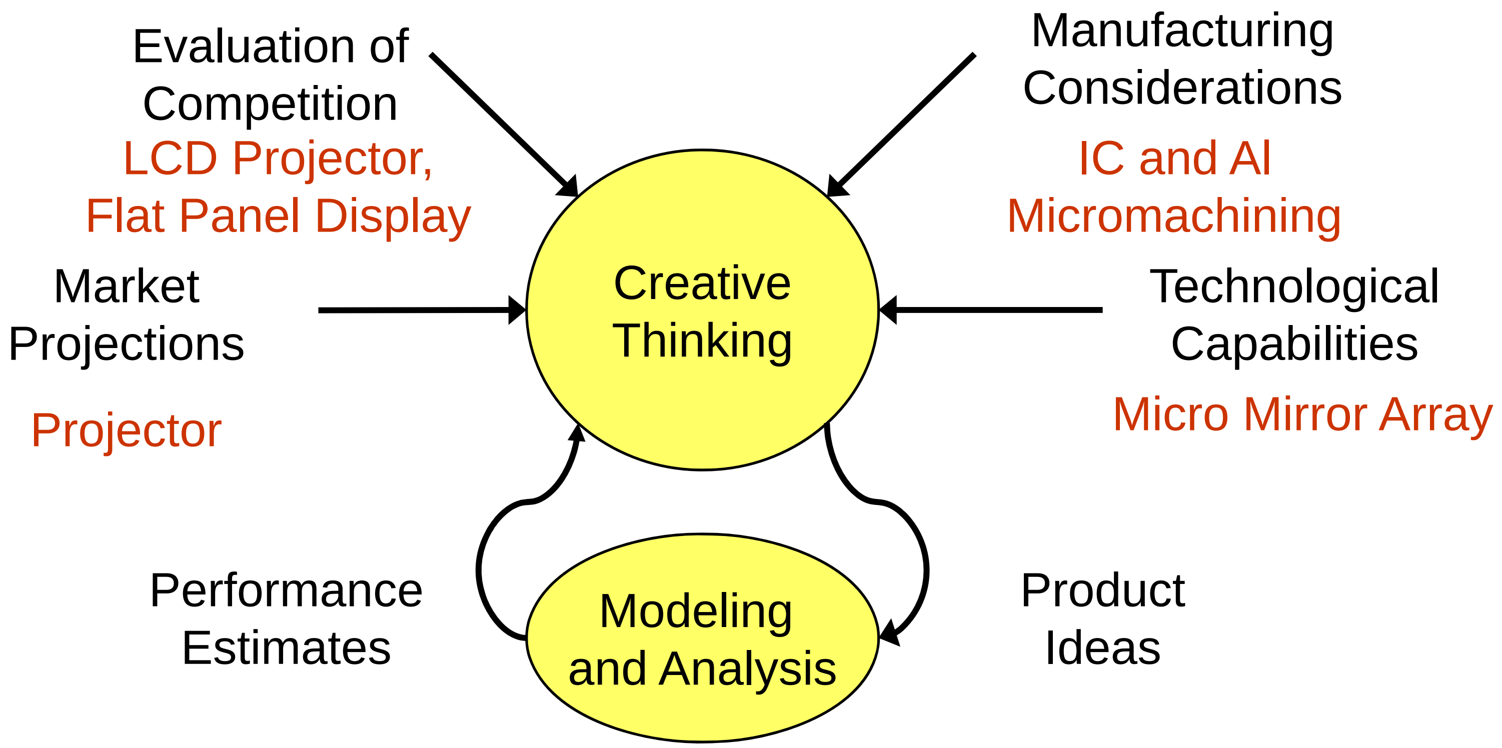


- High-level design issues and their relation to modeling and analysis

Technology-Driven Design

- In fast-developing technology like MEMS, **market identification and development often lags technology development.**
- Micro mirror array for display is example of a technology-driven design.
- TI has developed micro mirrors driven by electrostatic force since 1980.
- It is first necessary to prove that one can build a small mirror that can be tipped with electrostatic forces before one attempts to build an array of a million such mirrors to create a projection display.
- But, once one understands what kinds of device performance is possible with new technologies, market-driven design enters the picture.

Micro Mirror Array for Display



Evaluation of
Competition

LCD Projector,
Flat Panel Display

Manufacturing
Considerations

IC and Al
Micromachining

Market
Projections

Projector

Creative
Thinking

Technological
Capabilities

Micro Mirror Array

Performance
Estimates

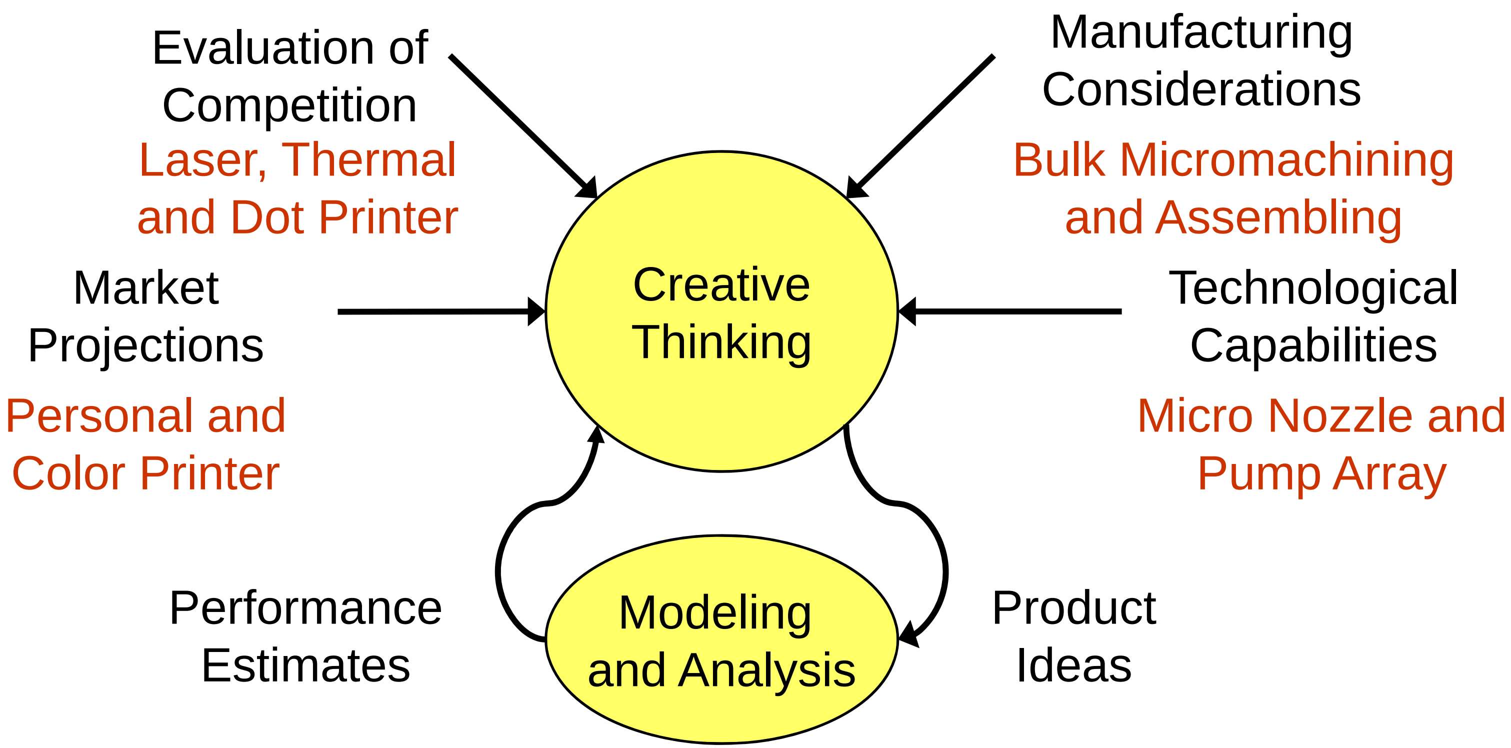
Modeling
and Analysis

Product
Ideas

Market-Driven Design

- Ink-jet printer is an example of market-driven design.
- The world was not sitting around with a specification for **ink-jet printing technology** waiting for someone to develop it.
- Instead, what the world wanted was faster high-resolution color printers, regardless of technology.
- Innovative individuals explored the ink-jet technology as a way of meeting this market need.
- Technology Demonstrations were required to see what was possible, out of which grew a capability that has had a revolutionary effect on the printing industry.

Ink-Jet Printer



Evaluation of Competition

Laser, Thermal and Dot Printer

Manufacturing Considerations

Bulk Micromachining and Assembling

Market Projections

Personal and Color Printer

Creative Thinking

Technological Capabilities

Micro Nozzle and Pump Array

Performance Estimates

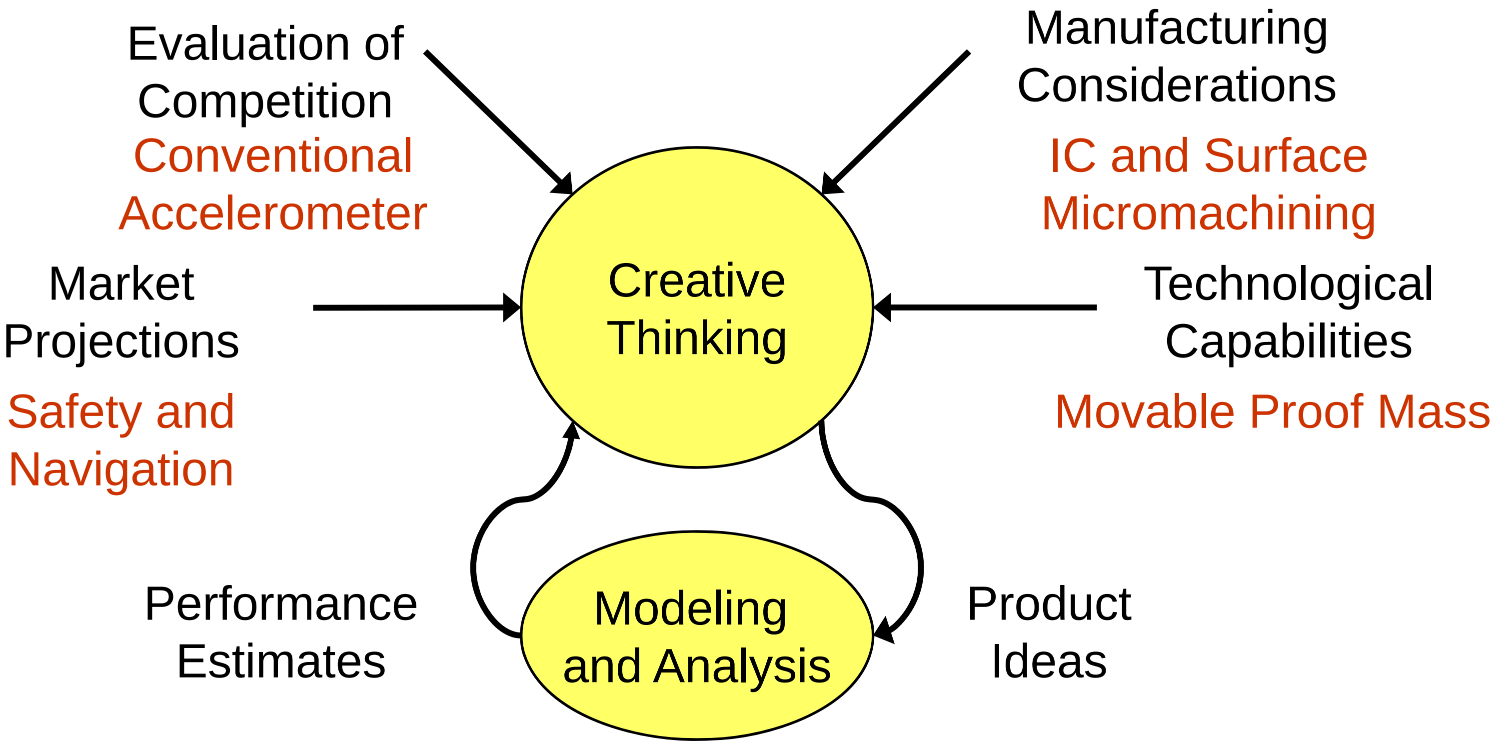
Modeling and Analysis

Product Ideas

Opportunistic Design

- Similarly, in the **automotive market**, the safety mandate for airbags in cars created a significant driving force for accelerometer development.
- One could use microfabrication technology to make freely moving capacitor plates that would respond to inertial forces.
- It predated the conception and design of a silicon automotive accelerometer.
- And while there has been significant competition from other methods for making this acceleration measurement, at this point the silicon accelerometer has basically displaced all other technological approaches for controlling airbag deployment.

Silicon Accelerometer



Evaluation of Competition

Conventional Accelerometer

Manufacturing Considerations

IC and Surface Micromachining

Market Projections

Safety and Navigation

Creative Thinking

Technological Capabilities

Movable Proof Mass

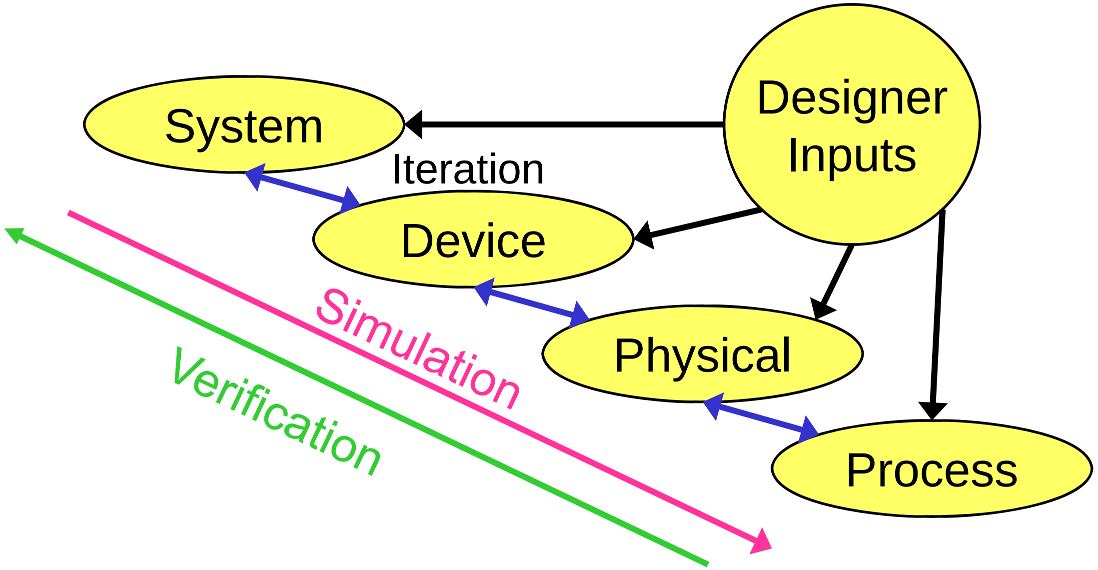
Performance Estimates

Modeling and Analysis

Product Ideas

Modeling Levels

- Modeling and analysis of devices and system is a complex subject.
- Modeling occurs at many levels and uses a variety of modeling paradigms, each one selected to be appropriate for that level.



Different modeling levels for microsystems

Four Modeling Levels - System

- **System, Device, Physical, Process**

- **System level:** This is the home of block-diagram descriptions and lumped-element circuit models, either of which can be used, and both of which lead to a coupled set of *ordinary differential equations (ODE's)* to describe the dynamical behavior behavior of the system.

Four Modeling Levels - Process

- At the bottom is **the process level**. This is where the process sequence and photomask designs for device manufacture are created.
- Process modeling at this level is a highly sophisticated numerical activity for which a number of commercial CAD tools have been developed, referred to generically as technology CAD or TCAD.
- For the MEMS designer, the importance of TCAD is that it can predict device geometry from the masks and process sequence.
- Because the material properties can depend on the detailed process sequence, the designer must know the proposed process in order to assign the correct material properties when modeling the device.

Four Modeling Levels - Physical

- **The physical level** addresses the behavior of real devices in the three-dimensional continuum.
- The governing equations are typically *partial differential equations (PDE’s).*
- Various analytical methods can be used to find closed-form solutions in ideal geometries but the modeling of realistic devices usually requires either approximate analytical solutions to the PDE’s or highly meshed numerical solutions.
- A variety of numerical modeling tools using either finite-element, boundary-element, or finite-difference methods are available for simulation at the physical level.

Four Modeling Levels - Device

- While meshed representations of the PDE's of continuum physics are useful in physical simulation, such representations are typically too cumbersome when dealing with entire devices and their associated circuitry.
- Instead, we go to **the device level** and create what are called *macro-models* or *reduced-order models* in a form that captures the essential physical behavior of a component of the system, and simultaneously is directly compatible with a system-level description.

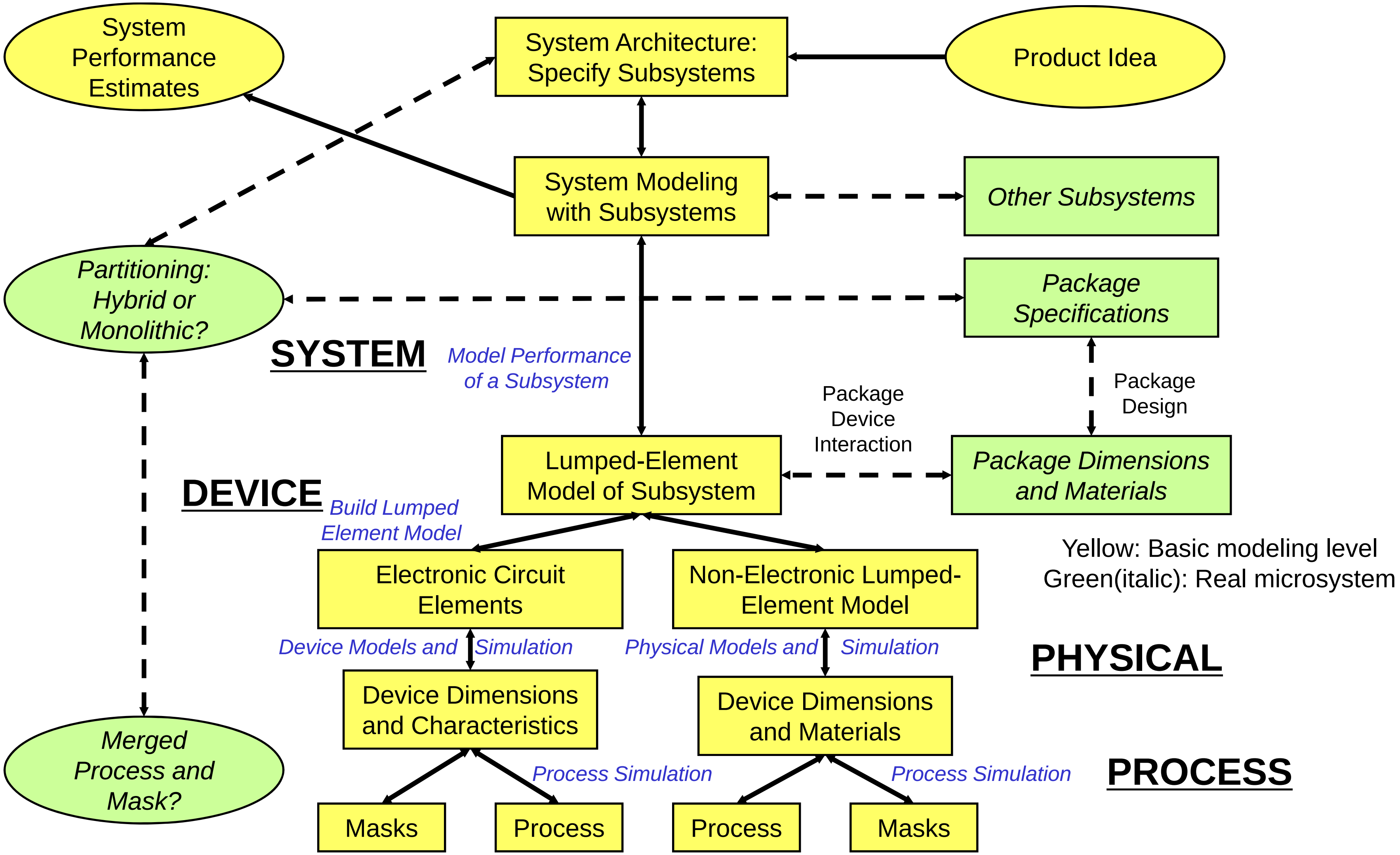
Macro Model

- **An ideal macro-model is analytic**, rather than numerical.
- **All the essential device behavior** in a form that permits rapid calculation and direct insertion into a system-level simulator.
- **Energetically correct**, conserving energy when it should, and dissipating energy when it should.
- **Correct dependence** on material properties and device geometry.
- **Both static and dynamic device behavior**, both for small amplitude (linear) excitation, and large-amplitude(presumably nonlinear) excitation.
- **Agree with the results of 3D simulation at the physical level**, **and with the results of experiments on suitable test structures.**
- **Not every model we shall encounter will reach this ideal.**

Analytical or Numerical?

- **Analytical first, numerical second.**
- Intelligent use of such numerical tools ultimately depends on a solid understanding of the underlying principles of the devices and their operation, and this understanding is best achieved by studying analytical (algebraic) models in detail.
- Furthermore, **the design insights provided by analytic models** are invaluable, especially the insights into the effects of varying either device dimensions or material properties.
- The advantage of using numerical CAD tools, especially at the physical level, is that **subtle second-order effects** can be accurately captured without requiring detailed analytical model development.

Modeling and Analysis



System Performance Estimates

System Architecture: Specify Subsystems

Product Idea

System Modeling with Subsystems

Other Subsystems

Partitioning: Hybrid or Monolithic?

Package Specifications

SYSTEM

Model Performance of a Subsystem

Package Device Interaction

Package Design

Lumped-Element Model of Subsystem

Package Dimensions and Materials

DEVICE

Build Lumped Element Model

Electronic Circuit Elements

Non-Electronic Lumped-Element Model

Yellow: Basic modeling level
Green(italic): Real microsystem

Device Models and Simulation

Physical Models and Simulation

PHYSICAL

Device Dimensions and Characteristics

Device Dimensions and Materials

Merged Process and Mask?

Process Simulation

Process Simulation

PROCESS

Masks

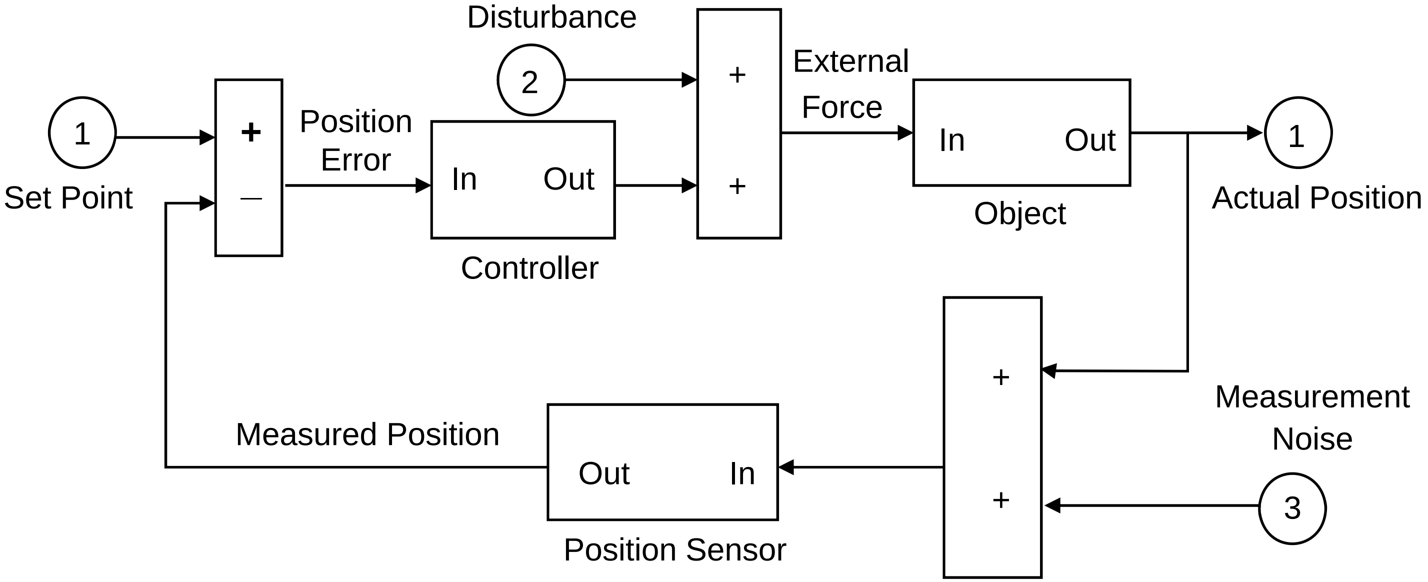
Process

Process

Masks

Example: A Position-Control System

- An example of a feedback position-control system to illustrate the modeling at various level.



A position-control system

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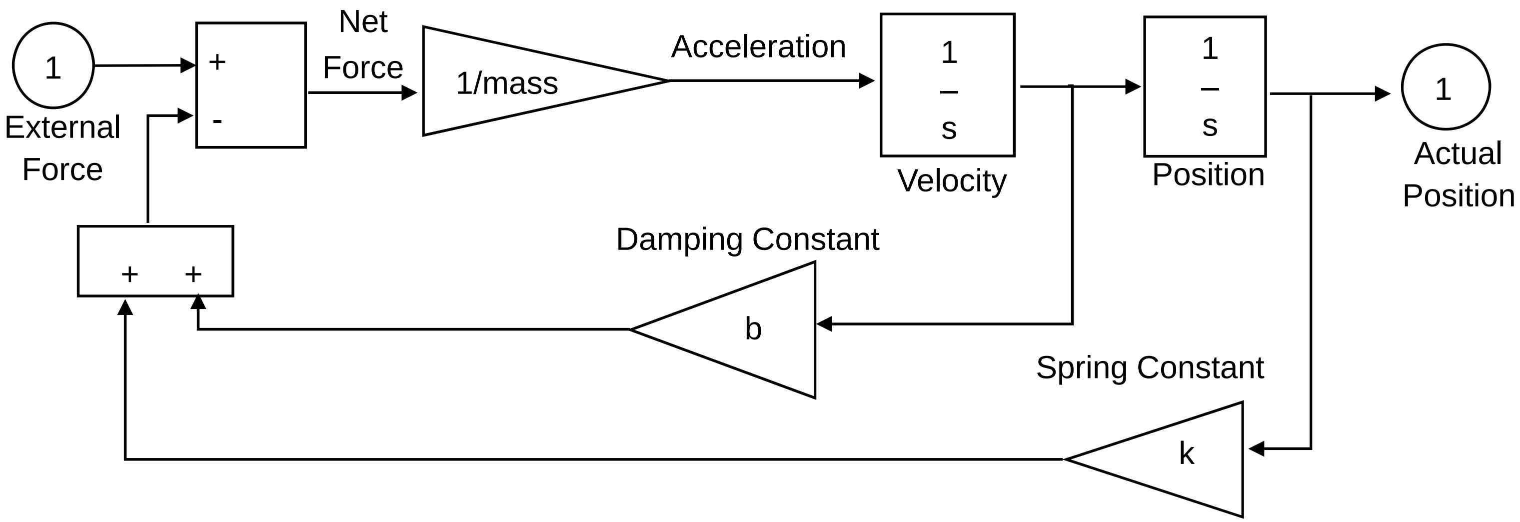
Object Subsystem

- We will consider the object itself, and treat it as an inertial mass, supported on a spring, with its motion damped by a linear dashpot.

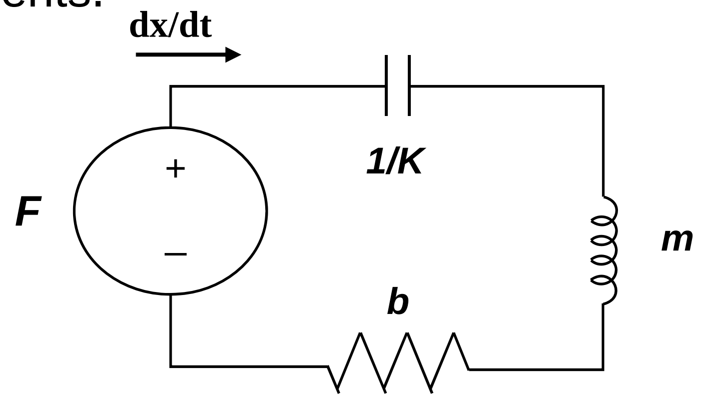


The “object” as a spring-mass-dashpot subsystem in block-diagram form

(continued)

Equivalent Circuit

- The spring-mass-dashpot subsystem with the equivalent circuit, in which the force ***F*** is analogous to **voltage**, the velocity of the object ***dx/dt*** analogous to **current**, with the **mass** represented by **an electrical inductor of value *m***, the **spring** by an **electrical capacitor with capacitance *1/k***, and the **dashpo**t with a **resistor of value *b*.**
- The equivalent circuit representation has advantages because the same modeling environment used for circuits (SPICE) can also be used for the mechanical elements.



The "object" represented as a spring-mass-dashpot subsystem in equivalent-circuit form