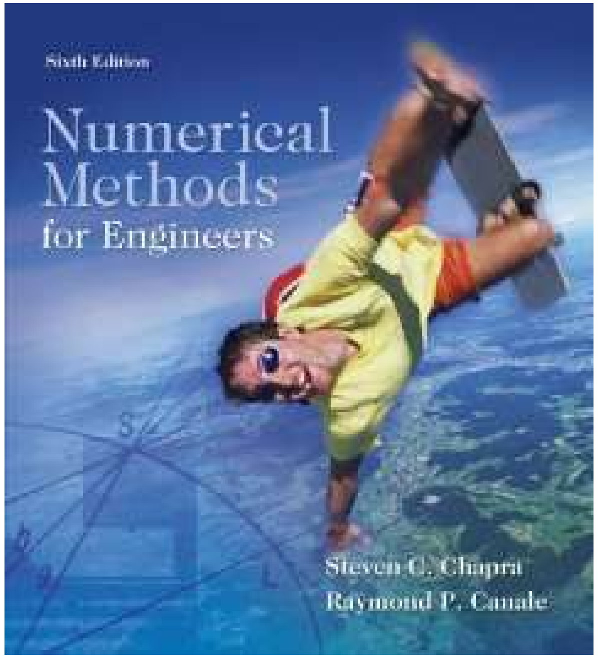
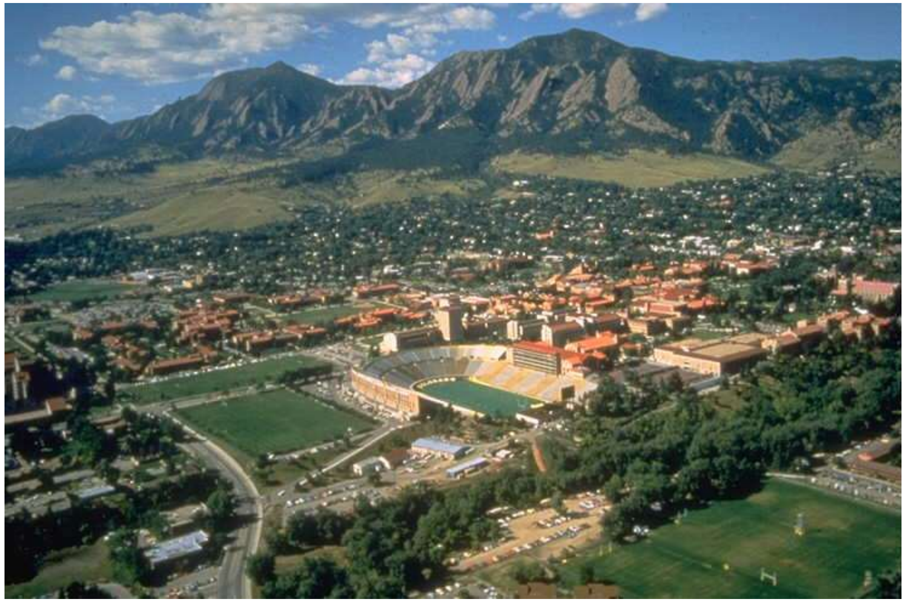
Reference Textbooks

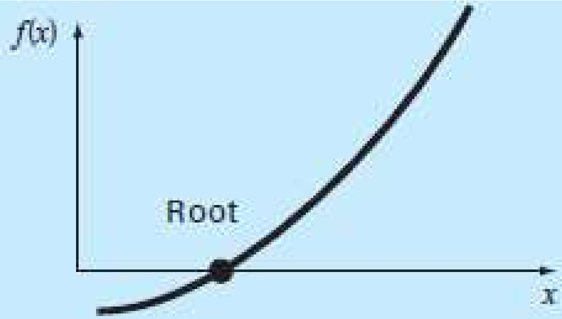




Reference Textbooks

- Engineering Mathematics
  - E. Kreyszig, Advanced Engineering Mathematics (10^{th} ed), 2011, Wiley
    - Ch.12 Partial Differential Equations (PDEs)
    - Part E. Numeric Analysis
    - Ch.19 Numerics in General
    - Ch.20 Numeric Linear Algebra
    - Ch.21 Numerics for ODEs and PDEs
- Electromagnetics
  - M.N.O. Sadiku, Elements of Electromagnetics (5^{th} ed), 2011, Oxford University Press
    - Ch.14 Numerical Methods

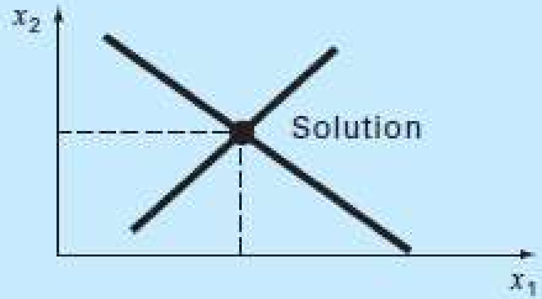
(*a*) *Part 2:* Roots of equations
Solve $f(x) = 0$ for x.



(*b*) *Part 3:* Linear algebraic equations
Given the a's and the c's, solve

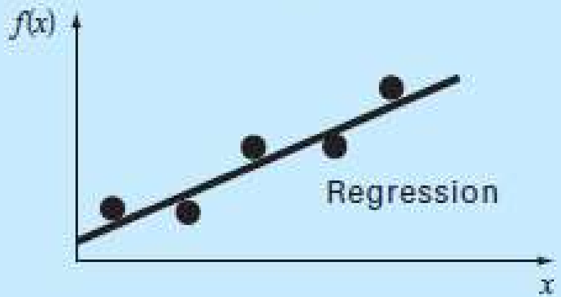
$$a_{11}x_1 + a_{12}x_2 = c_1$$
$$a_{21}x_1 + a_{22}x_2 = c_2$$

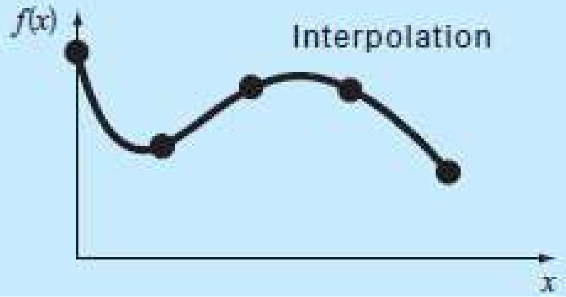
for the x's.



(*c*) *Part 4:* Optimization
Determine x that gives optimum $f(x)$.

(*d*) *Part 5:* Curve fitting

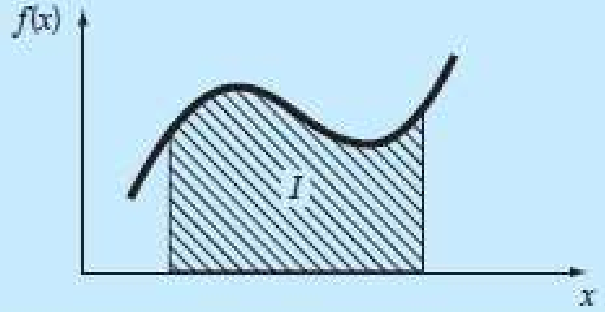




(*e*) *Part 6:* Integration

$I = \int_a^b f(x)\,dx$

Find the area under the curve.



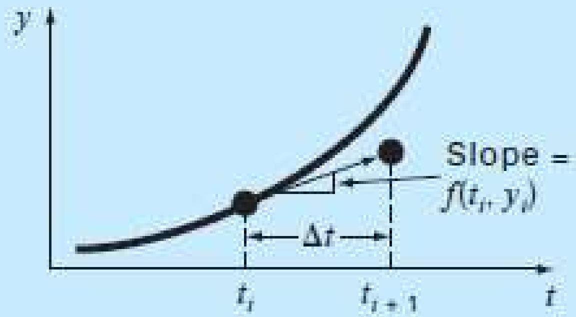
(*f*) *Part 7:* Ordinary differential equations

Given

$$\frac{dy}{dt} \simeq \frac{\Delta y}{\Delta t} = f(t, y)$$

solve for y as a function of t.

$$y_{i+1} = y_i + f(t_i, y_i)\,\Delta t$$

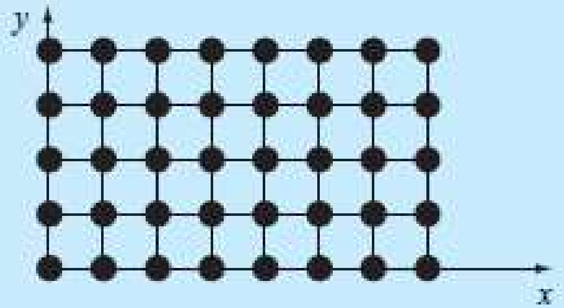


(*g*) *Part 8:* Partial differential equations

Given

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = f(x, y)$$

solve for u as a function of x and y



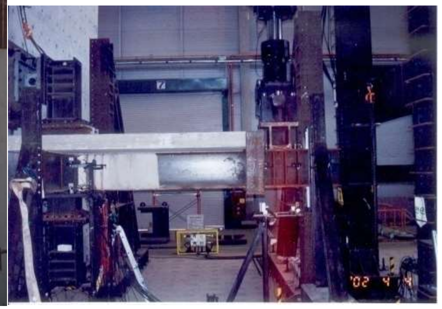
분석 프로세스

자연 현상

안전성, 경제성 확보

모델링

실험 모델



수학 모델

이론

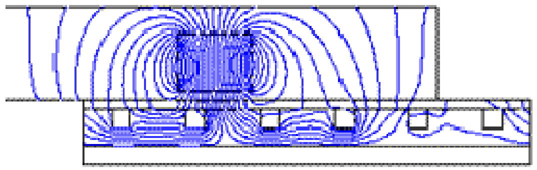
수치해석

CAE의 개념

- Computer-Aided Engineering
  - **해석**(지배방정식 수치해법), 시뮬레이션, 설계, 제조, 기획, 진단, 수리 등과 같은 엔지니어 업무를 지원하는 정보기술
  - 설계업무지원 CAE: 물리현상, 품질, 최적화, CAD와 통합
  - 제조업무지원 CAE: 사출성형, 스탬핑, 단조, 캐스팅
- 근사적 수치해석
  - 유한차분법, **유한요소법**, 유한체적법, 경계요소법 등
- 설계자가 많이 사용하는 CAE
  - **구조해석**(응력:강도, 변형:강성), 열해석, 고유치해석

CAE의 필요성(1)

- CAE없이는 알 수 없는 경우: 본질적으로 불가능
  - 재료 내부의 응력/자속 흐름
  - 전자파 전달
- CAE없이는 불가능한 경우: 실제상 불가능한 현상
  - 기술적으로 재현할 수 없는 극한 환경
    - 온도가 100만℃, 중력이 만 배 되었을 때 어떠한가?
  - 초미소(원자단위), 초거대(우주단위)
  - 이론물리학의 검증
- 규제상의 문제: 핵분열 시뮬레이션
- 계산량이 많아 수작업으로 힘든 문제
  - 각종 최적설계

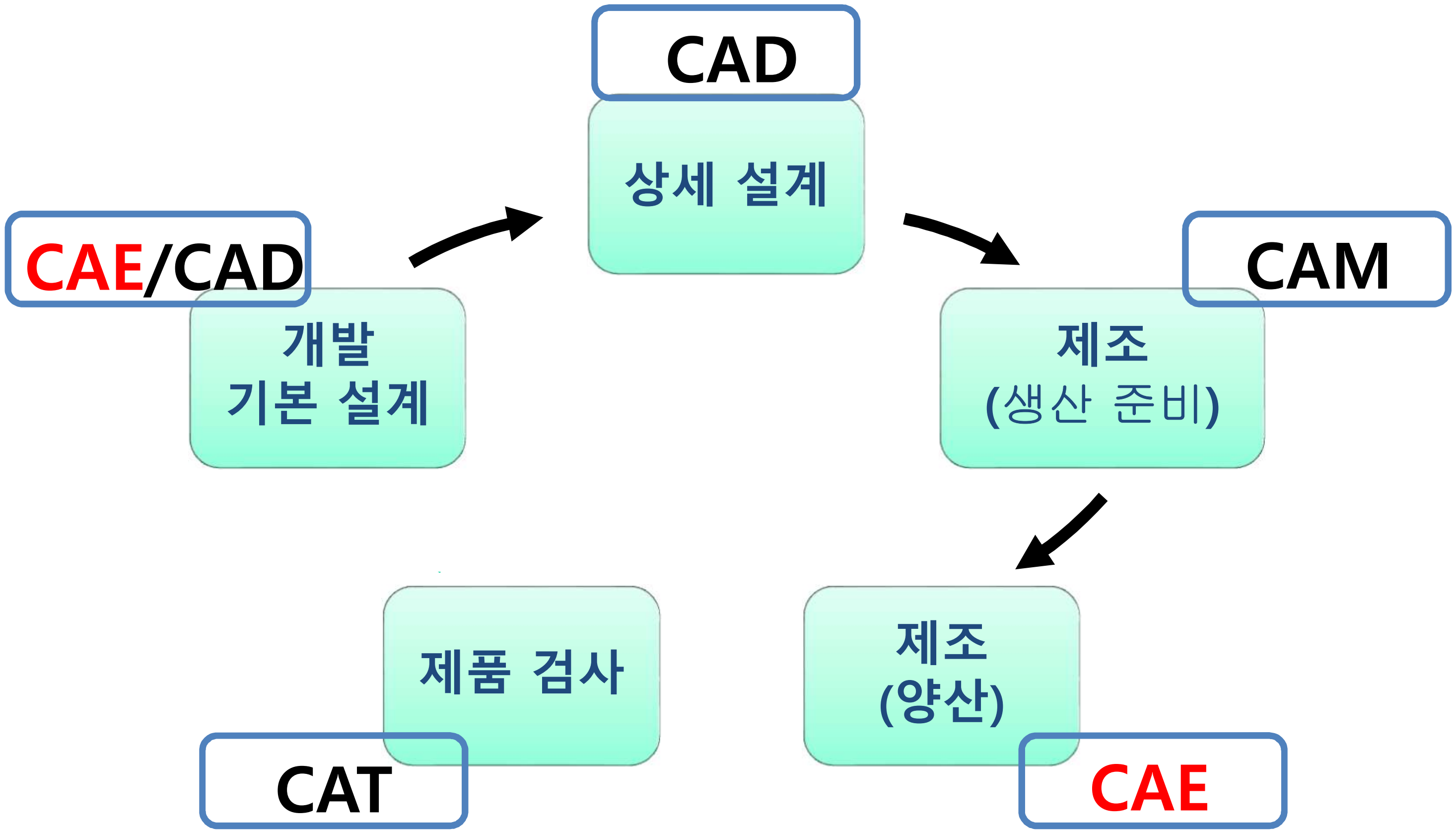


CAE의 필요성(2)

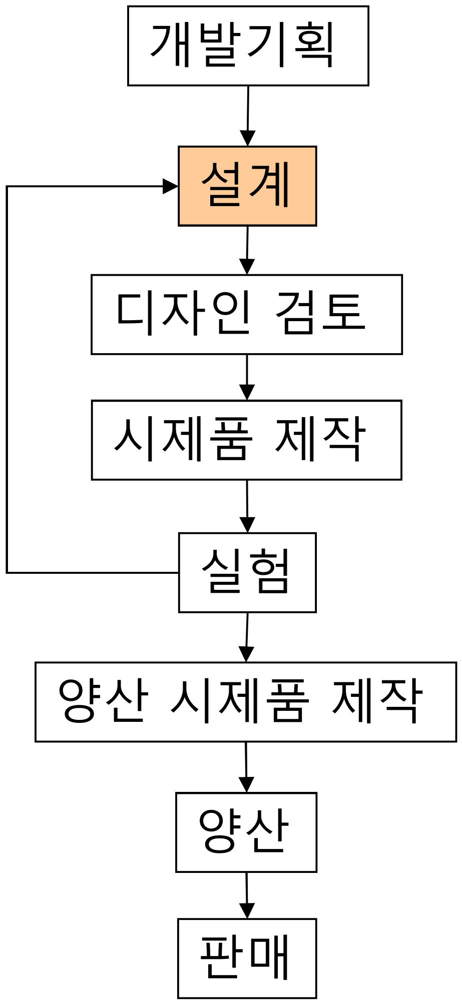
- CAE없이는 곤란한 경우
  - 지구상의 재현이 곤란한 극한환경: 진공, 무중력상태
  - 위험을 동반한 실험: 눈길에서 시속 200km/h로 자동차가 급정지하는 거동
  - 엔진을 한계로 회전시킬 때 거동
  - 충돌 순간: 백만분의 1초 거동
- 막대한 실험비용이 소요되는 경우
  - 자동차 충돌, 핵실험, 시간단축가능
- 제3자를 이해시키는 경우
  - 이해하기 쉬운 후처리로 전문가 이외에도 결과를 이해 가능, 프리젠테이션 효과 큼

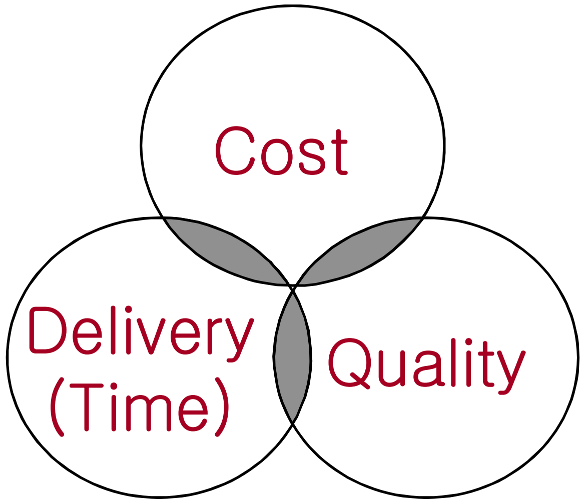
생산공정의 디지털화 (Digital Manufacturing)

- CAD/CAE/CAM과 같은 컴퓨터에 의한 디지털 정보기술을 개발, 설계, 제조, 검사 등의 생산 프로세스에 활용



CAE 역할 : 제품개발 프로세스





제품개발 초기단계에서 CAE 도입 장점

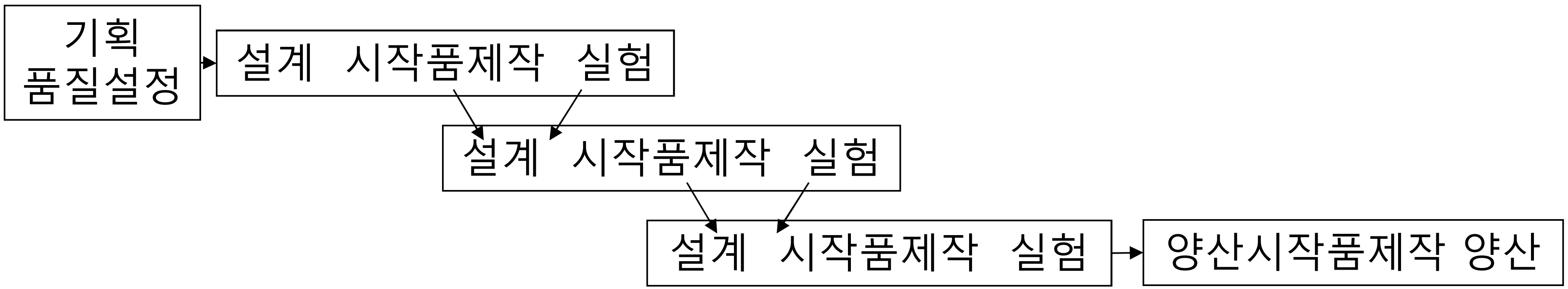
– 시제품 제작 이전에 설계안 평가 가능

– 설계변경의 자유도가 비약적으로 증대

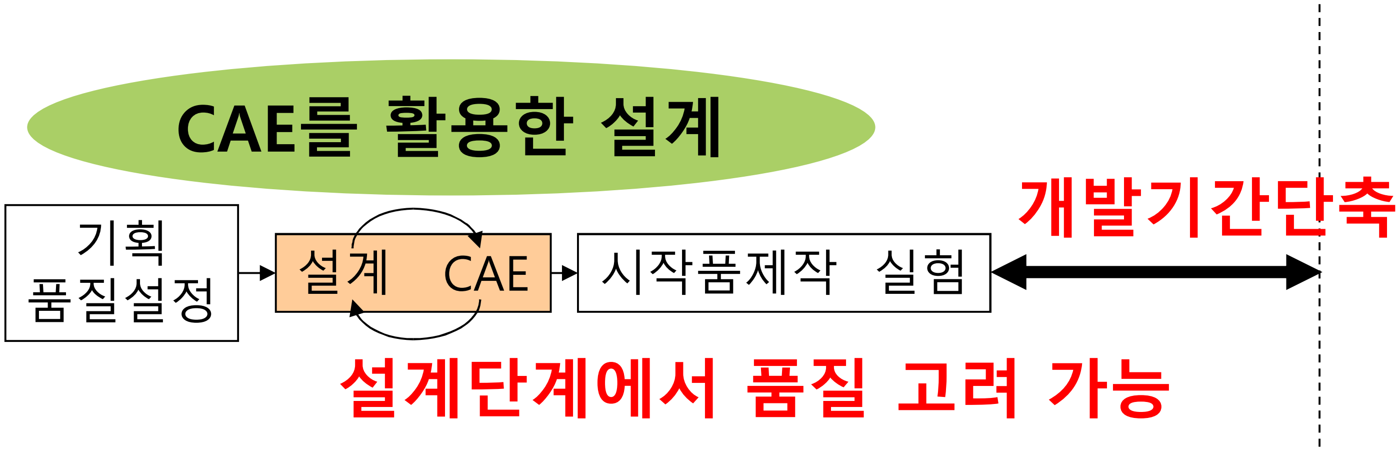
– 시간 및 비용 절감

CAE 역할 : 개발기간 단축

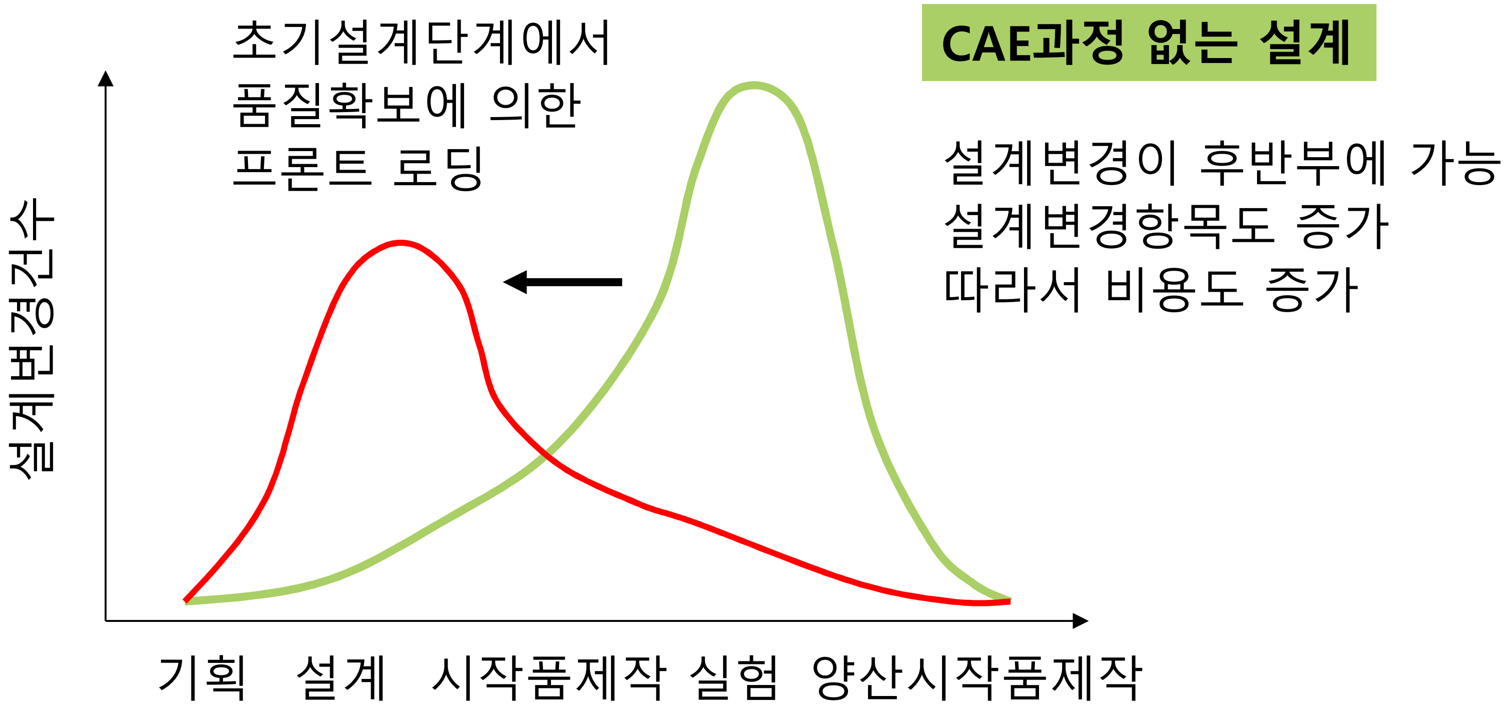
기존 설계



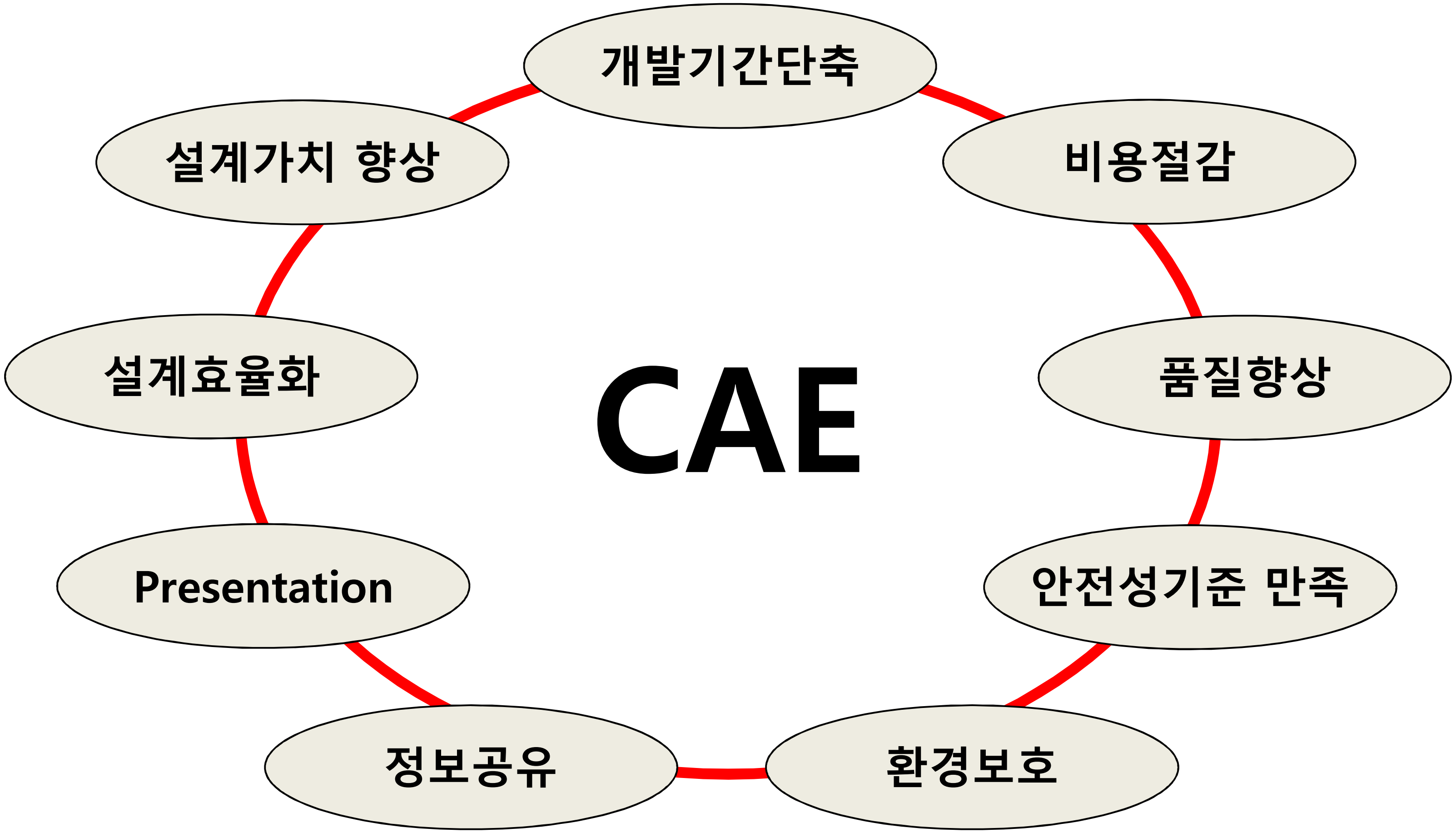
CAE를 활용한 설계



CAE 역할 : 프론트 로딩


초기설계단계에서
품질확보에 의한
프론트 로딩
CAE과정 없는 설계
설계변경이 후반부에 가능
설계변경항목도 증가
따라서 비용도 증가
설계변경건수
기획 설계 시작품제작 실험 양산시작품제작

CAE 역할 : 장점

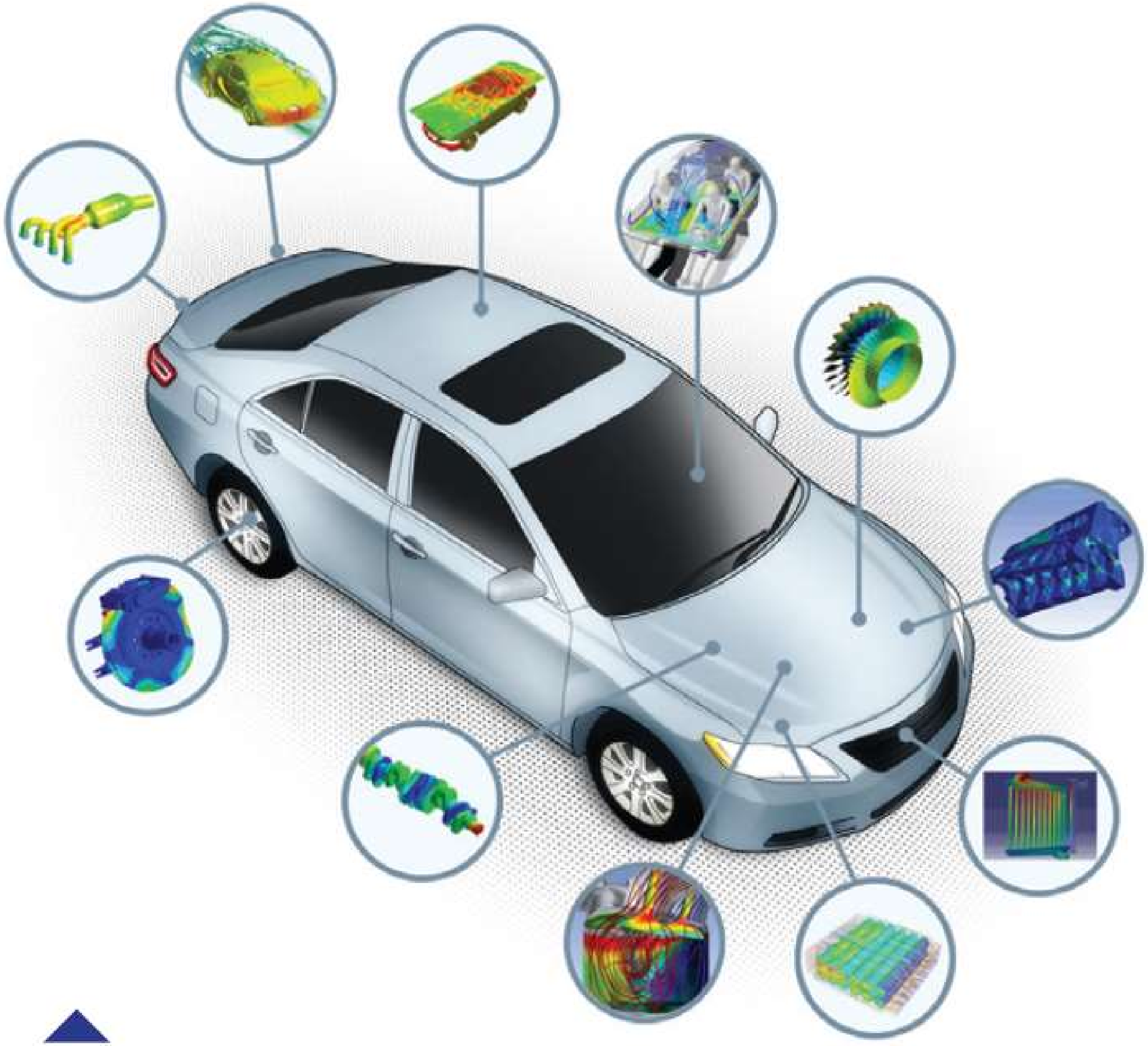


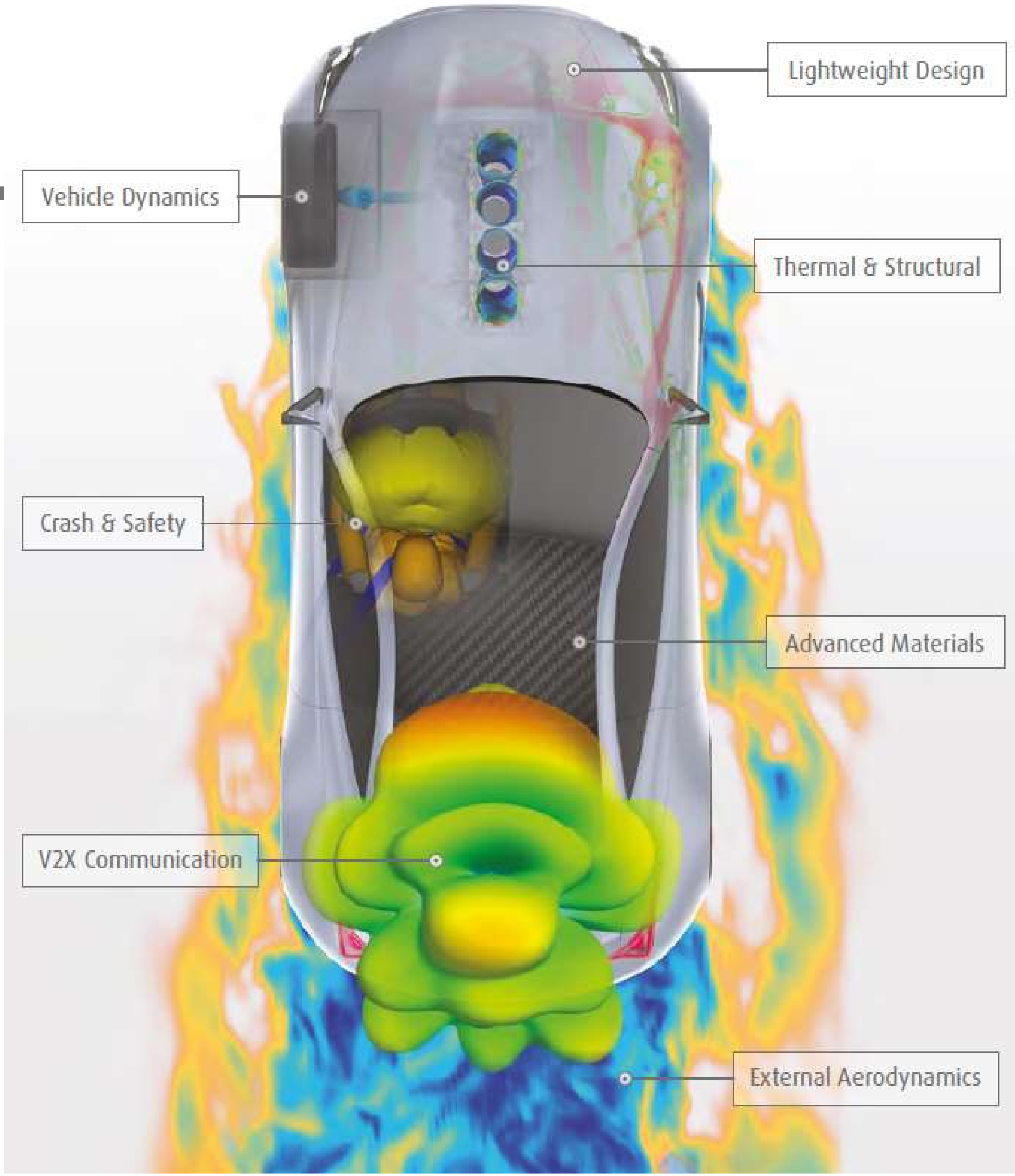
개발기간단축
설계가치 향상
비용절감
설계효율화
CAE
품질향상
Presentation
안전성기준 만족
정보공유
환경보호

CAE 적용분야

- 기계 구조물: 미세한 반도체 회로~항공기/플랜트
- 통신제어분야: 로직, 알고리즘 개발
- 구조역학, 유체역학, 기계역학, 열공학, 광학, 음향공학, 원자력공학, 항공우주공학, 전자공학, 정밀공학, 바이오, 케미컬공학, 환경공학, 생체공학, 금융공학

자동차 CAE




Lightweight Design
Vehicle Dynamics
Thermal & Structural
Crash & Safety
Advanced Materials
V2X Communication
External Aerodynamics

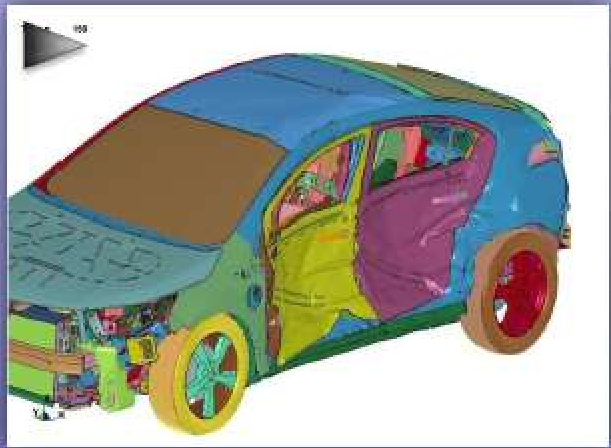
자동차 CAE

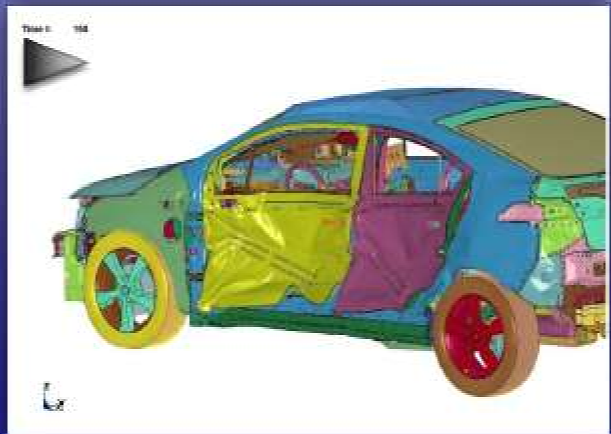
Test

50 kph IIHS Side Impact Deformable Barrier

CAE accurately predicts physical test

CAE Model





Physical Test

Computer-Aided Engineering (CAE)

- Wikipedia: broad usage of computer software to aid in engineering tasks
  - coined by Jason Lemon, founder of SDRC in the late 1970s
  - better known today by the terms CAx and PLM
- CAE tools
  - software tools that have been developed to support these activities
  - analyze the robustness and performance of components and assemblies
  - simulation, validation, and optimization of products and manufacturing tools

CAE Areas

- Stress analysis on components and assemblies using FEA (Finite Element Analysis)
- Thermal and fluid flow analysis Computational fluid dynamics (CFD)
- Multibody dynamics(MBD) & Kinematics
- Analysis tools for process simulation for operations such as casting, molding, and die press forming
- Optimization of the product or process
- Safety analysis of postulate loss-of-coolant accident in nuclear reactor using realistic thermal-hydraulics code

Three Phases in CAE

- Pre-processing
  - defining the model and environmental factors to be applied to it (typically a finite element model, but facet, voxel and thin sheet methods are also used)
- Analysis solver
  - usually performed on high powered computers
- Post-processing of results
  - using visualization tools

Classification

- Mechanics
  - Theoretical
  - Applied
  - Computational
  - Experimental

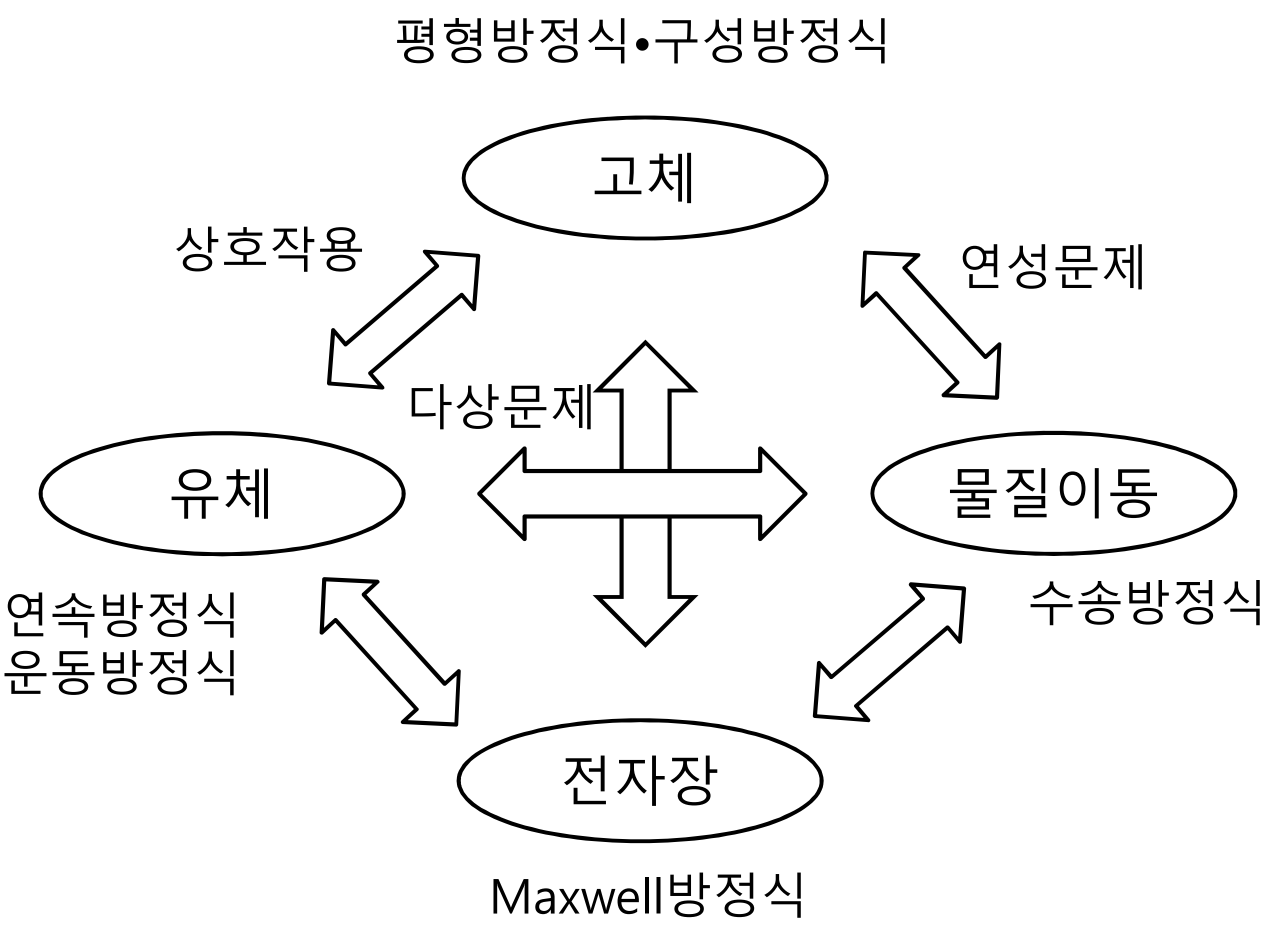
- Computational Mechanics —physical scale→
  - Nanomechanics
  - Micromechanics
  - Continuum mechanics
    - Solids and Structures
    - Fluids
    - Multiphysics
  - Systems

- Computational Solid and Structural Mechanics —inertia effects→
  - Statics
    - Time Invariant
    - Quasi-static
      - Linear
      - Nonlinear
  - Dynamics

Computational Mechanics

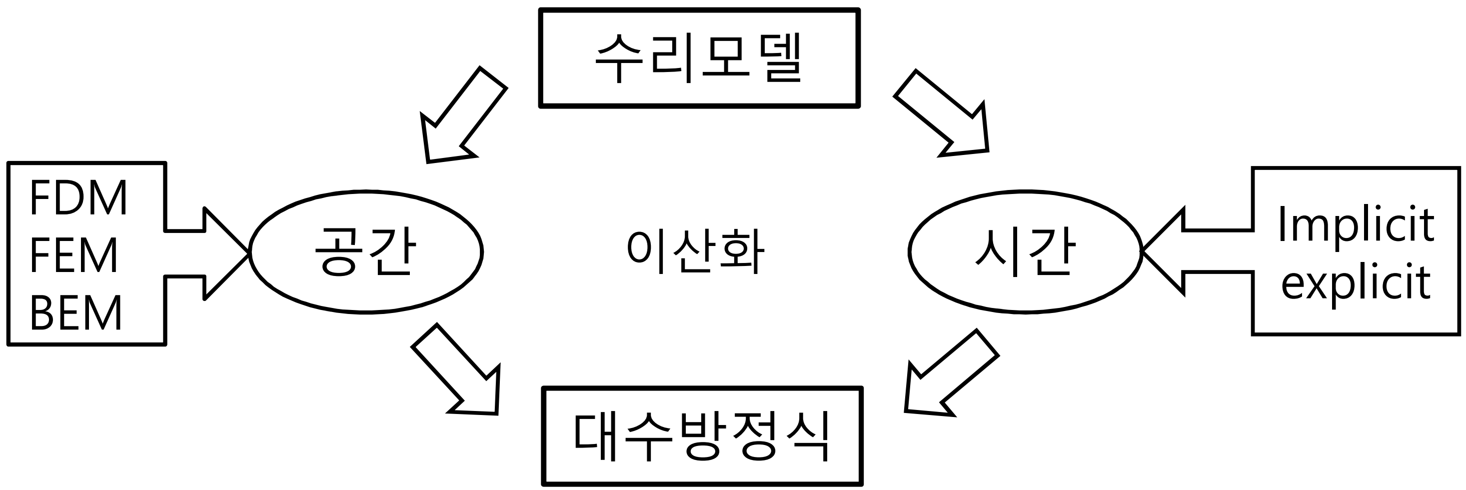
- 이론역학(theoretical mechanics), 실험역학(experimental mechanics)과 함께 역학분야의 하나로 컴퓨터시뮬레이션에 의해 역학현상을 해명하기 위한 학문
- 역학계산과 같은 단순한 보조수단으로 컴퓨터사용은 포함하지 않고 현상의 지배방정식을 근거로서 보다 적극적으로 컴퓨터를 이용하여 역학현상을 이해하고 설명하려는 학문
- 편미분방정식으로 주어진 지배방정식의 이산화해석방법의 개발과 공학문제로의 적용

물리현상을 지배하는 대표적인 방정식



이산화 해석 방법

- 유한차분법(FDM: Finite Difference Method)
- 유한요소법(FEM: Finite Element Method)
- 유한체적법(FVM: Finite Volume Method)
- 경계요소법(BEM: Boundary Element Method)

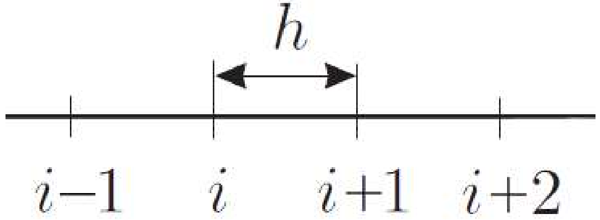


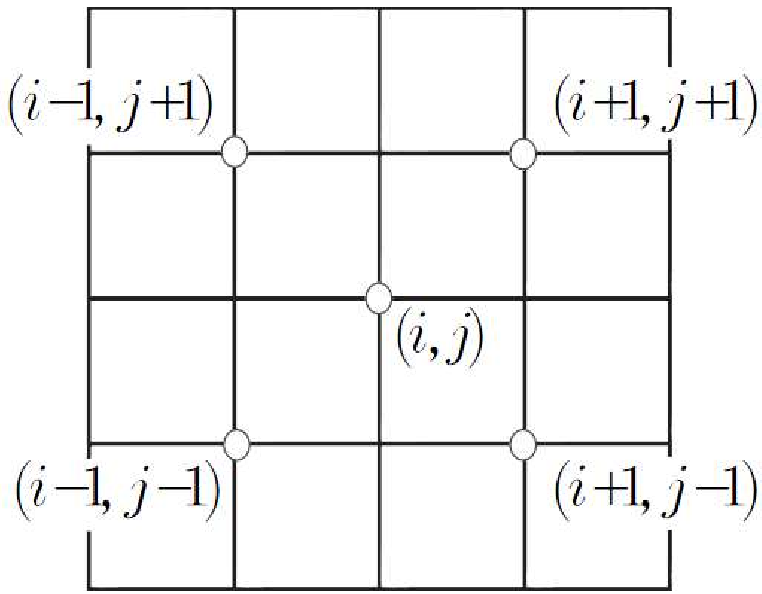
유한차분법(FDM: Finite Difference Method)

- 단순하지만 범용성이 크기 때문에 수치해석의 초기부터 현재까지도 폭넓게 사용되고 있는 방법
- 정방격자에 의해 분할하는 것이 원칙이므로 복잡한 경계형상의 근사가 충분하지 못함

$$\frac{du}{dx} = \lim_{h \to 0} \frac{u(x+h) - u(x)}{h} \approx \frac{u(x+h) - u(x)}{h}$$

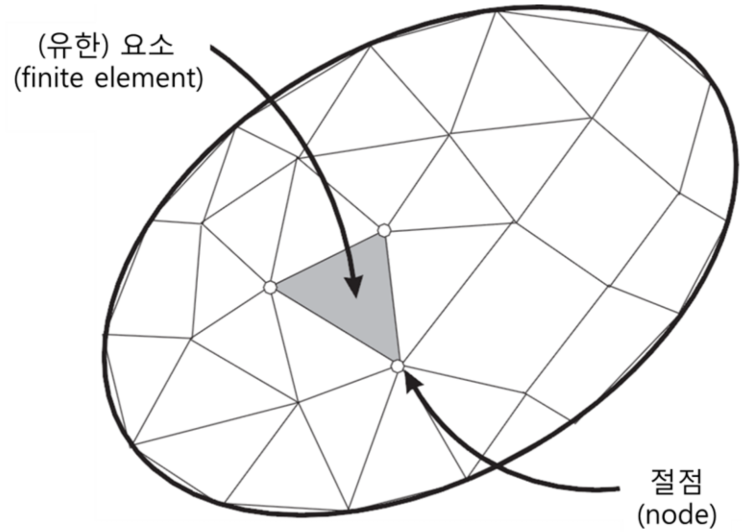
$$\frac{d^2u}{dx^2} \approx \frac{\dfrac{u_{i+2} - u_{i+1}}{h} - \dfrac{u_{i+1} - u_i}{h}}{h} = \frac{u_{i+2} - 2u_{i+1} + u_i}{h^2}$$





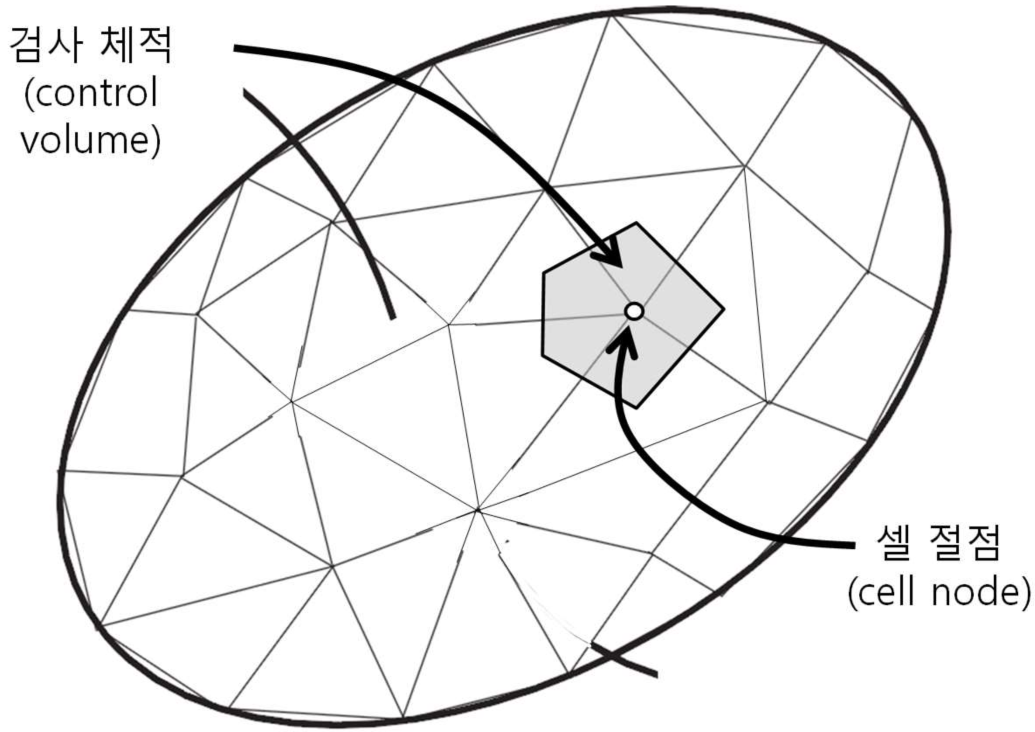
유한요소법(FEM: Finite Element Method)

- 변분원리→가중치잔차법: 광범위한 미분방정식에 대한 해석방법으로 급속히 보급
- 영역을 많은 부분영역으로 분할하고 그 영역 내에 있어서 단순한 함수의 중첩에 의해 미지량을 근사
- 미분방정식을 적분형식(약형식)으로 변환하여 간접적으로 해를 구함
- 요소형상은 임의이므로 (구조격자일 필요는 없다) 차분법과 비교하여 복잡한 구조나 경계가 있어도 비교적 쉽게 요소분할이 가능



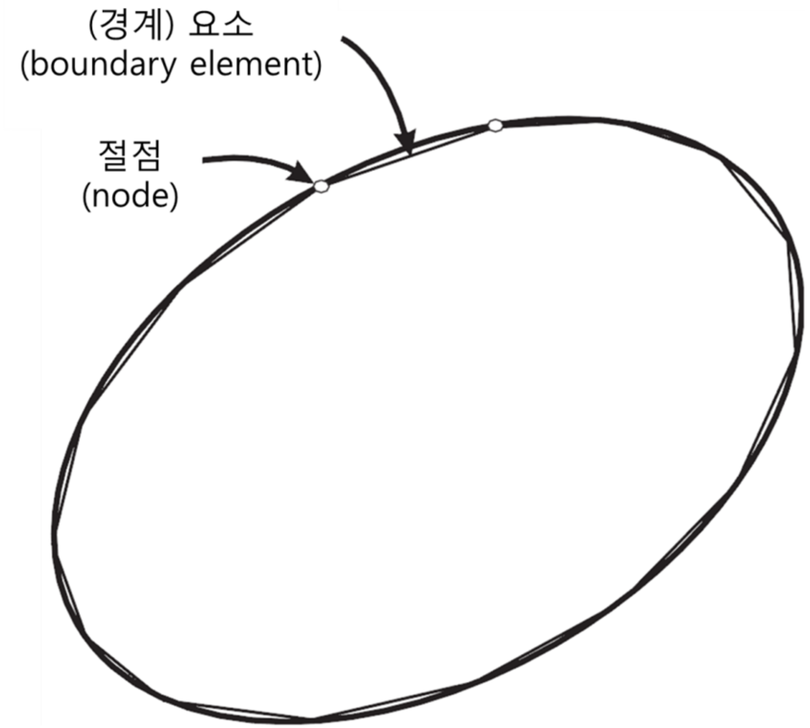
유한체적법(FVM: Finite Volume Method)

- 비구조격자에 기초한 유체역학을 위하여 개발된 방법
- 셀이라고 하는 다수의 임의형상의 작은 영역으로 분할하고, 지배방정식을 셀 절점을 중심으로 한 컨트롤 볼륨 내에서 적분
- 컨트롤 볼륨 내에서 보존법칙이 완전히 만족되는 특징



경계요소법(BEM: Boundary Element Method)

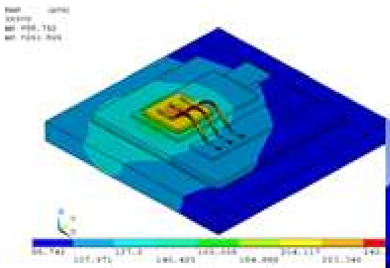
- 미분방정식을 일단 경계적분방정식으로 표현하여 수치적으로 근사해를 구하는 방법
- 요소분할: (2차원) 영역경계만으로 충분 (3차원) 영역경계면
- 지반 내의 파동전파 등과 같이 무한영역을 다뤄야 하는 문제나 응력집중 등과 같이 해에 특이성이 있는 문제의 해석에도 적합



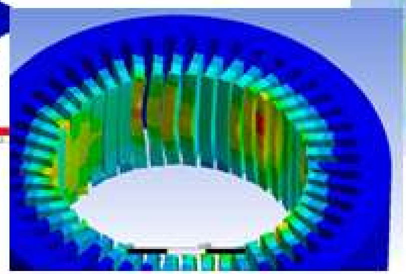
SolidWorks Simulation

개별영역 → 복합영역

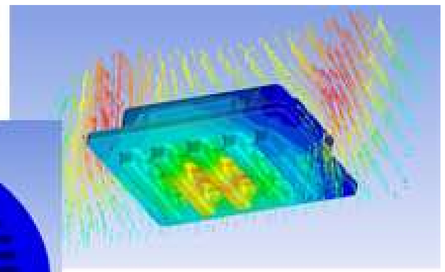
실험기반으로 개발하는 것과 비교하여
시간과 비용 모두 절감



파워모듈의
전류-열전달-구조해석



IPM모터의 자장-구조연성해석

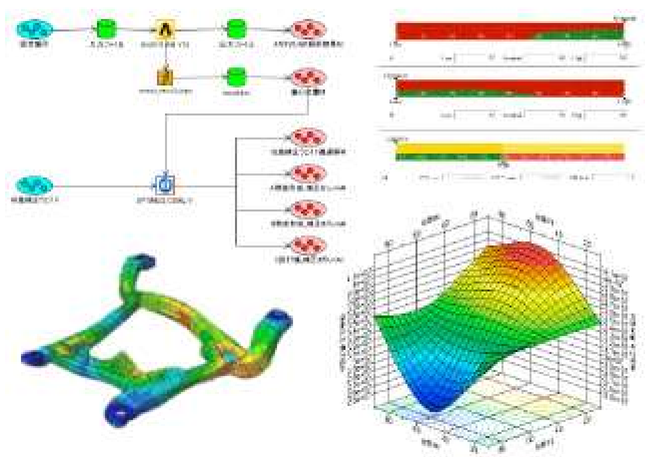


ECU의 열유체-구조연성해석

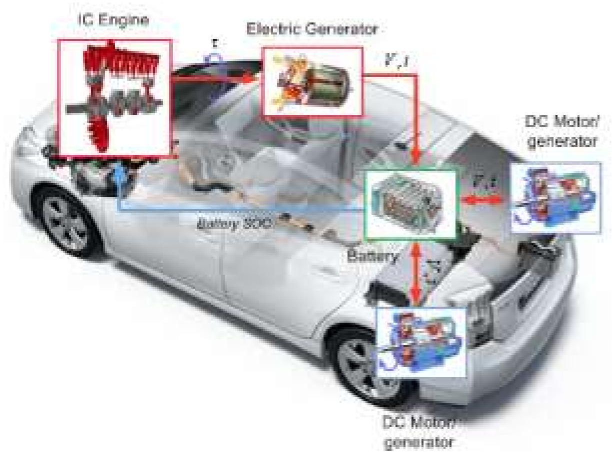
3D-3D연계(연성해석, 멀티피직스)가 가능, 상호작용을 고려
해석모델이 복잡, 해석시간이 오래걸림

복합영역의 새로운 접근방법

통합최적화



1D-CAE



Simulation at the Systems Level

- Objectives
  - Inform design choices
  - Provide validation results
  - Investigate the effects of a design change in one component on the rest of the system
  - Provide designers with system level insight
  - Functional validation of the system at an early stage of design
  - Reduce the number of design iterations significantly
  - Understand how they will function under operating conditions, identifying potential problems, and developing solutions before going to the prototyping stage
- Requirements
  - Go beyond individual components and a single physics
  - Describe how all components interact as a system

Model-Based Systems Engineering (MBSE)

Early Concept Phase
System Requirements
Functional Specification
Functional Model & Simulation

Development of a Functional Model is Critical in the Early Concept Phase

Subsystem modeling
Mechanical/Electrical/Hydraulics
Control Design

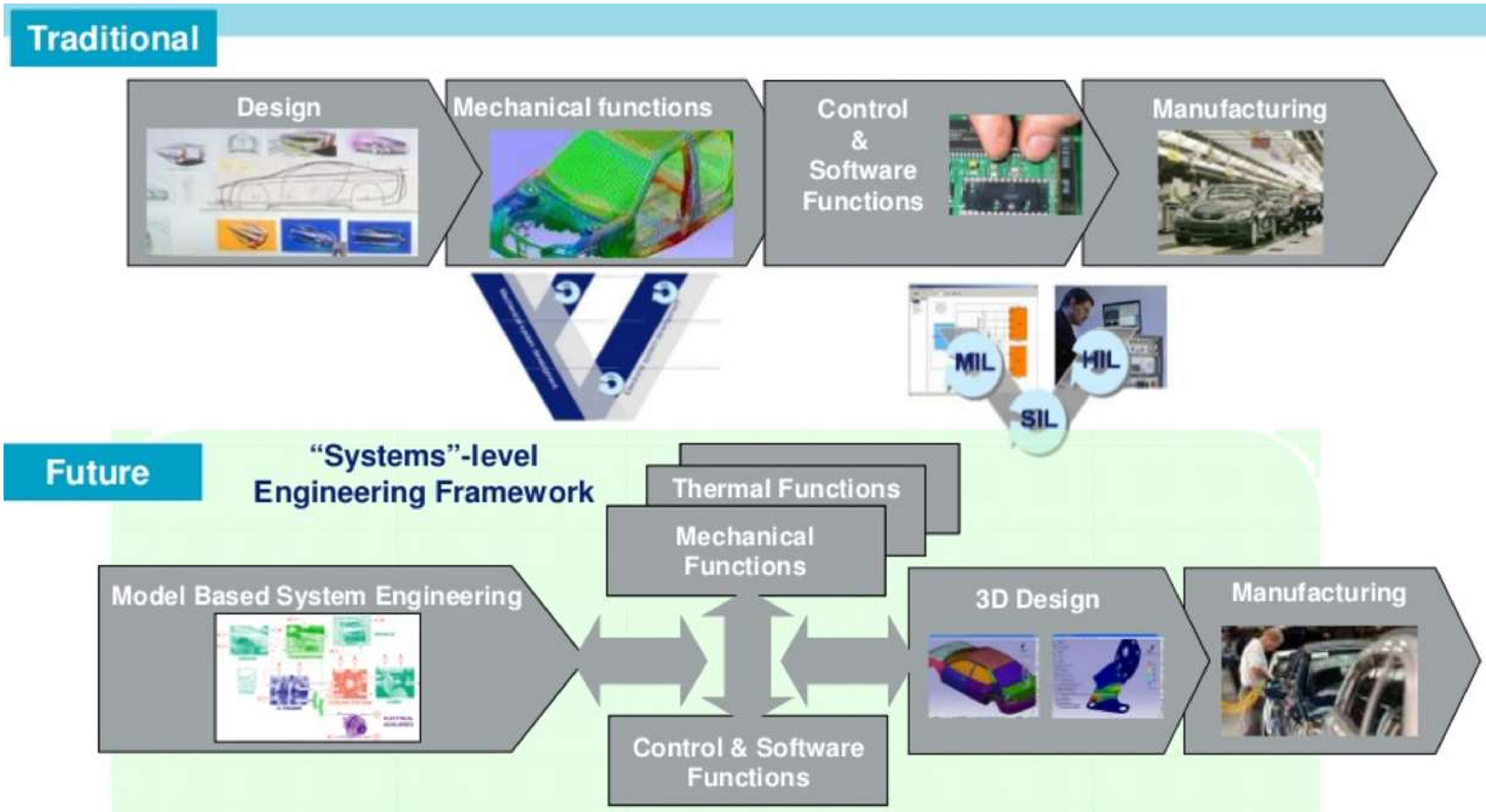
System-level Integration & Validation
Virtual Prototyping
Functional Validation
Parametric Studies

Early System Validation Shortens Development Lifecycle

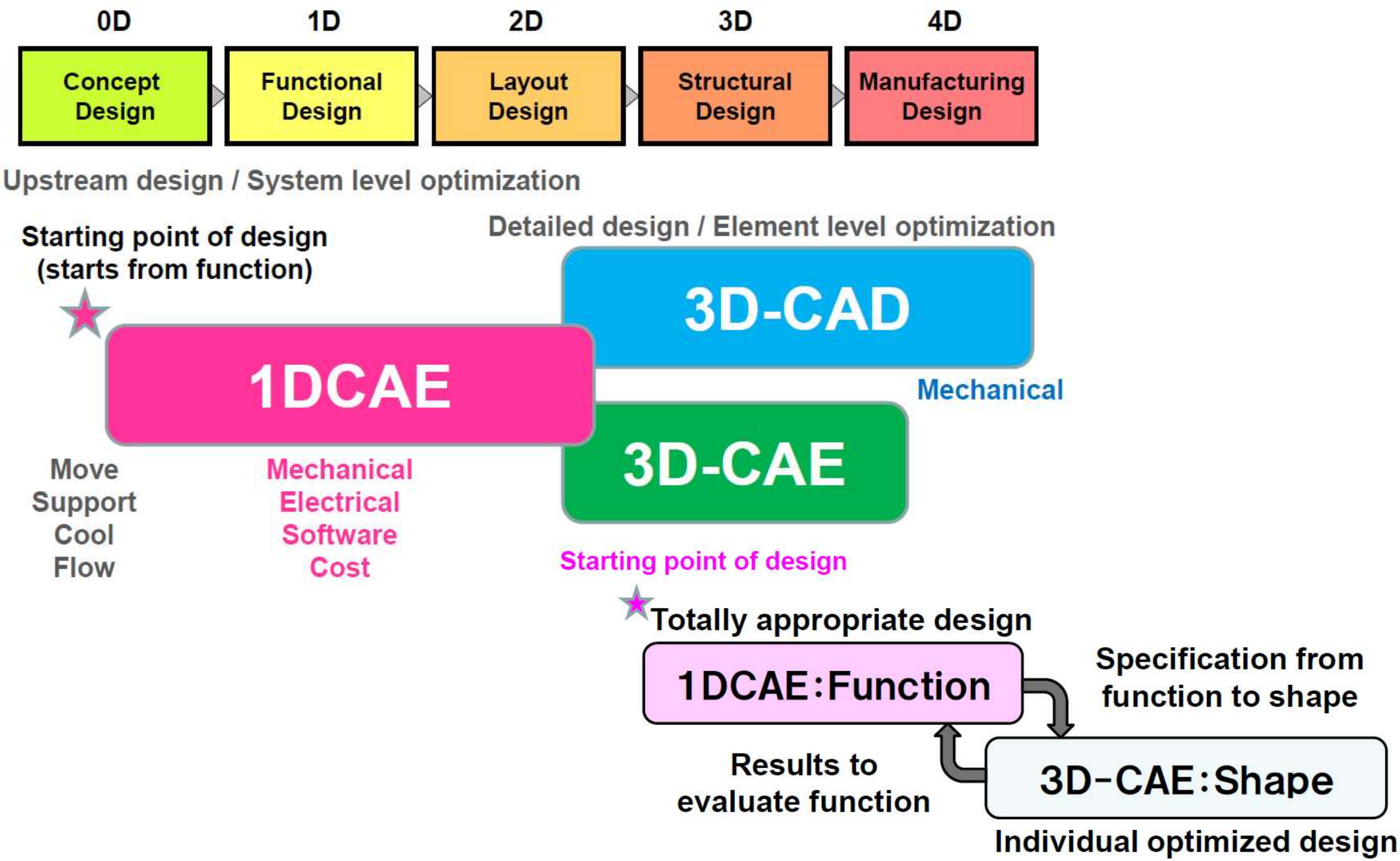
Design Optimization
Importance/Sensitivity Analysis
Design of Experiments
Multi-objective Optimization
Process integration (PIDO)…

Design Reuse and Modularity Essential to Engineering Systems Development

Paradigm Shift: Model Based Development Process



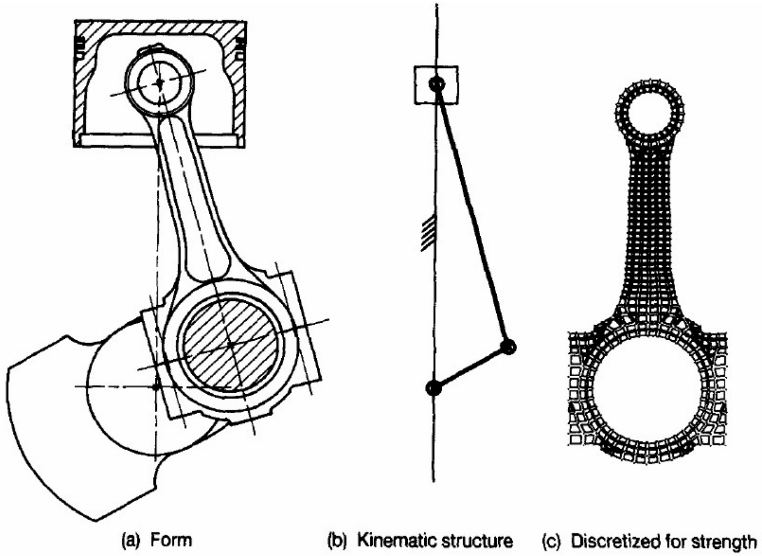
Design Process based on 1D CAE



Ohtomi, International Modelica Conference(2015)

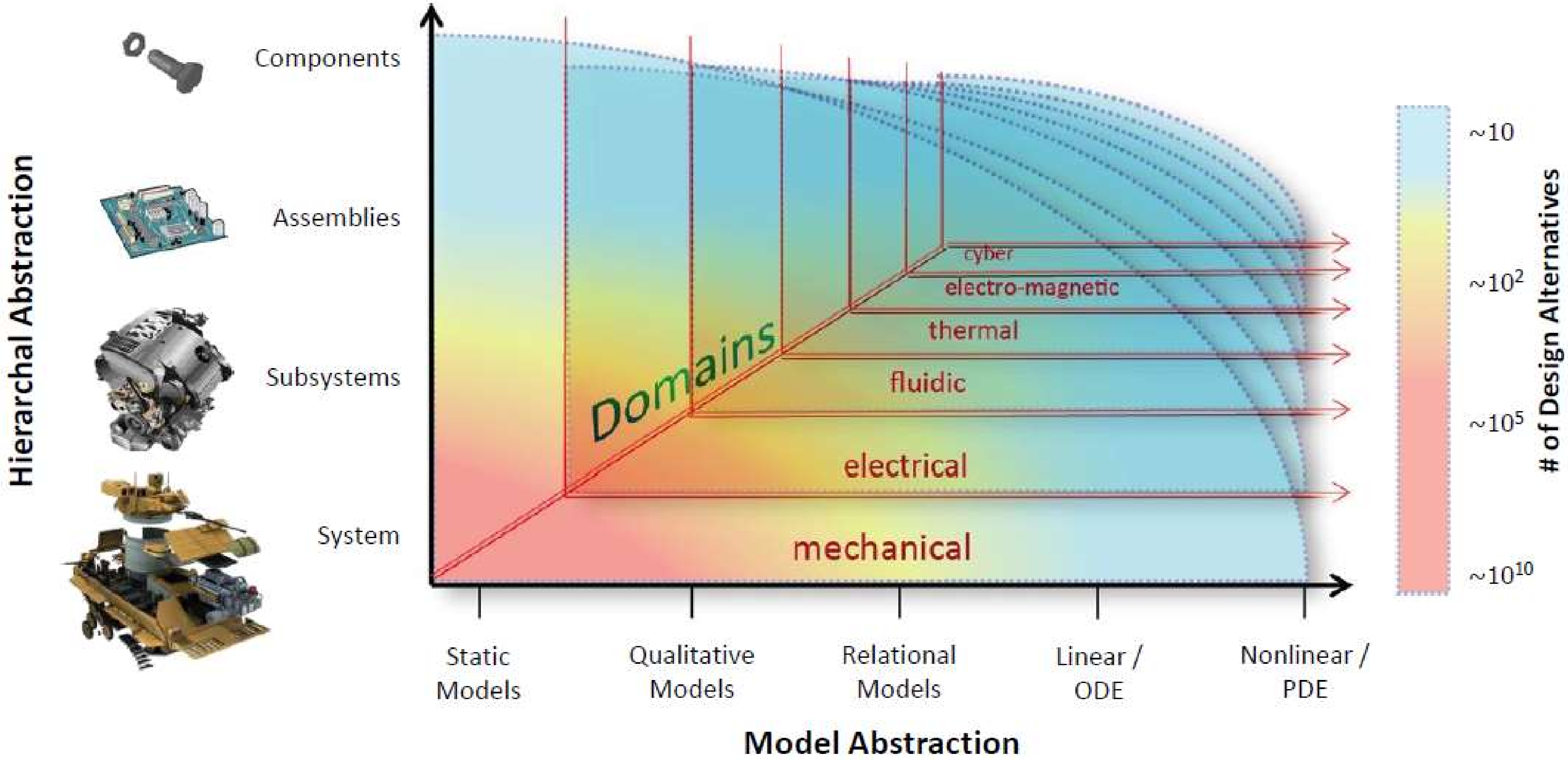
Different Models of Same Component

- Models can be either abstractions or representations of reality that facilitate the understanding of complexity



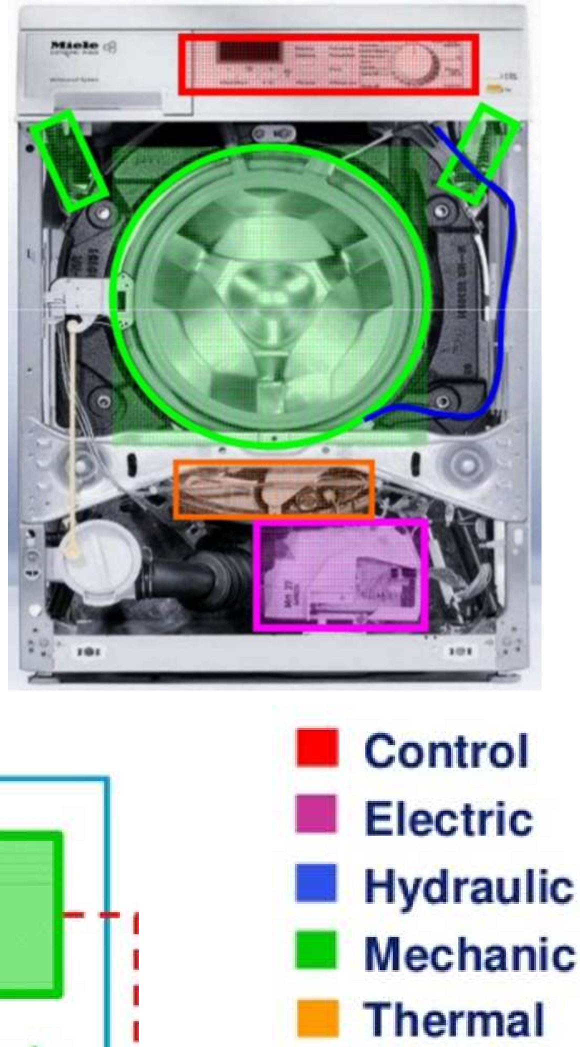
- Component Modeling
  - Combine components from multi-domain component library
  - Physics based equations and/or Modelica code to create custom components
  - Experimental data as lookup tables

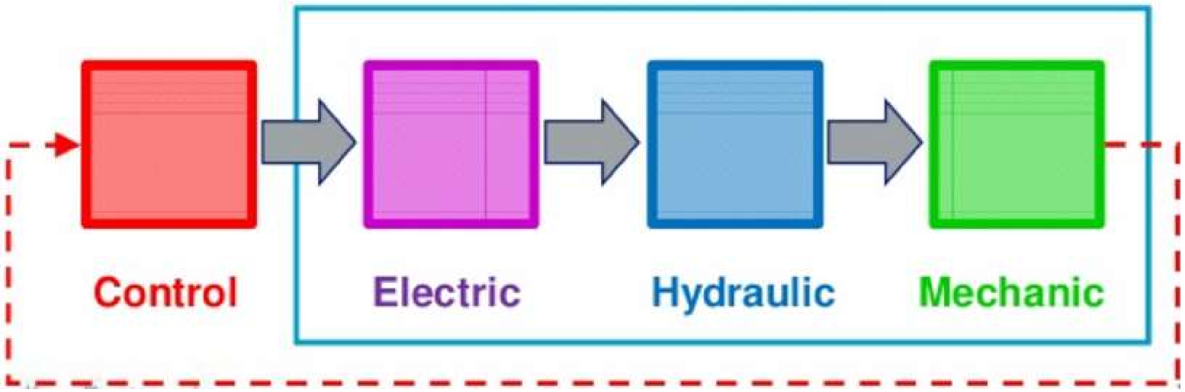
Hierarchal and Model Abstraction



System Simulation: Example

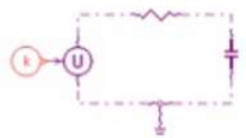
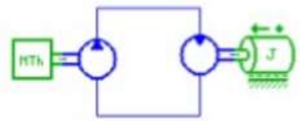
- Usual design issues:
  - Is the electric motor powerful enough?
  - What is the time response of the system?
  - Is there any risk of vibration?
  - How to optimize the control design?
- Key words:
  - Multi-physics with power exchange
  - Dynamic system (function of time)
  - Physical system model = Plant model





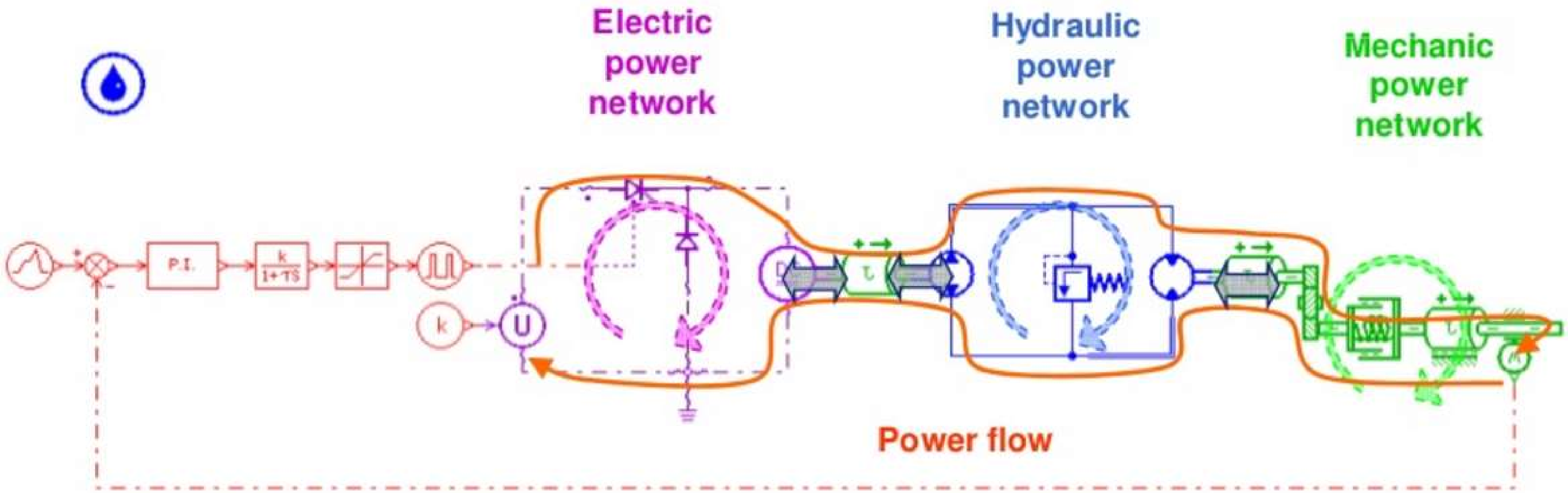
Abstraction Level

- Equations are usually written as time dependent
- Computing state derivative of variables to assess transient evolution
- Equations are represented by readable objects

	Equations	Physical Icon Representation
Mechanics	$M*dx/dt^2 = F - R\,dx/dt - Kx$ $s^2 + 2 \cdot z \cdot \omega_n \cdot s + \omega_n^2 = 0$	
Electric	$U = R*I$ $dU/dt = I/C$	
Hydraulics	$Q = displ*\Omega$ $T = displ*\Delta P$	

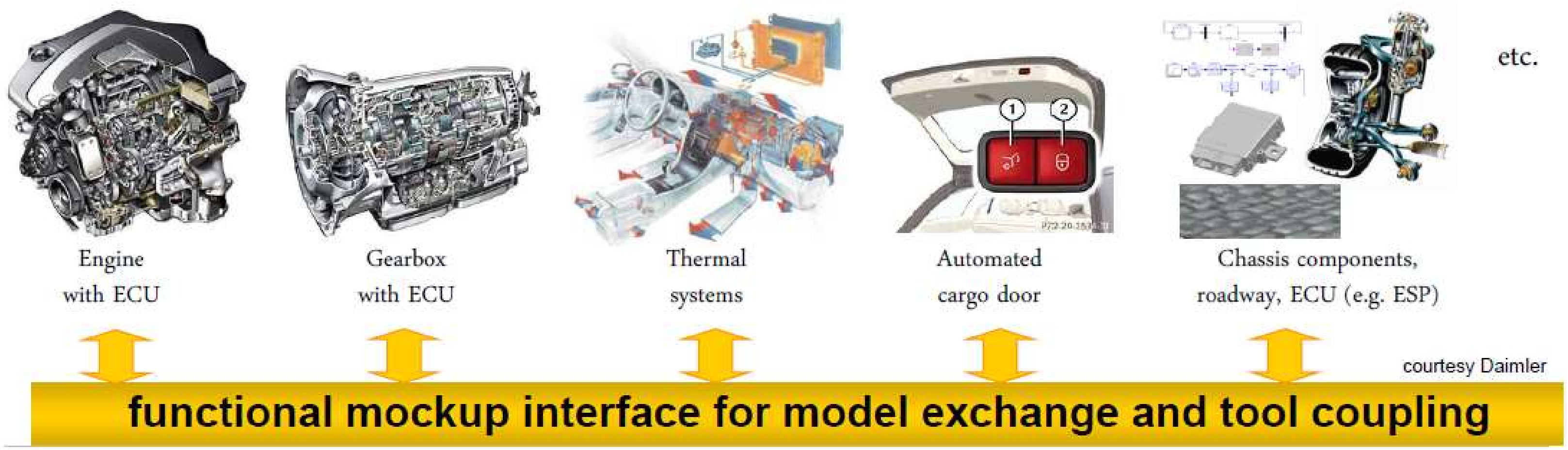
Power Flow within dynamic system

- System simulation is linked to the power flow and power conservation within a dynamic system
- Each power networks can be modeled using different physics with gates for sub-system connections



Convergence of Model-based Design Tools

- Increasing demand for implementation of 3D finite-element models in system-level tools
- Growing interest in co-simulation
- Functional Mockup Interface (FMI)
  - www.fmi-standard.org (Open Standard)
  - 2008-2011, 29 partners, 30M€, headed by Daimler AG
  - Improved Software/Model/Hardware-in-the-Loop Simulation, of physical models from different vendors



Benefits

Drive innovation

- Explore a wider range of ideas and solutions
- Early validation of technical feasibility
- Test and compare new ideas via simulation

Streamline process

- Reduce design cycle by virtual system integration
- Increase reusability through knowledge capitalization

Improve quality

- Improved product behavior predictability
- Better collaboration between principles
- Tighter integration of functions to build a final product

Reduce costs

- Reduce development costs with fewer physical prototypes
- Minimize risk on test beds
- Reduce product's breaks and failures

Drawbacks

- It is not the answer in isolation from other practices
- It is hard to model non-functional requirements
- The model can be a barrier to understanding for some stakeholders
- Effective MBSE requires a disciplined and well trained project team and a mature process approach