Optimal Design of System Architectures

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Outline

- Background
- Past Research
  - Hybrid Electric Powertrain Architecture Design
  - Design of Modular Architectures for Vehicle Fleets
  - Design Using Game Platforms

Background

Sabancı Üniversitesi

B.S. Mechatronics Engineering, 2011
Sabanci University, Istanbul

UNIVERSITY OF MICHIGAN

M.S. Mechanical Engineering, 2013
PhD. Mechanical Engineering, 2015
University of Michigan, Ann Arbor

Research Fellow and Adjunct Lecturer
University of Michigan, Ann Arbor

Agenda for Design Research

Design: Decision making process

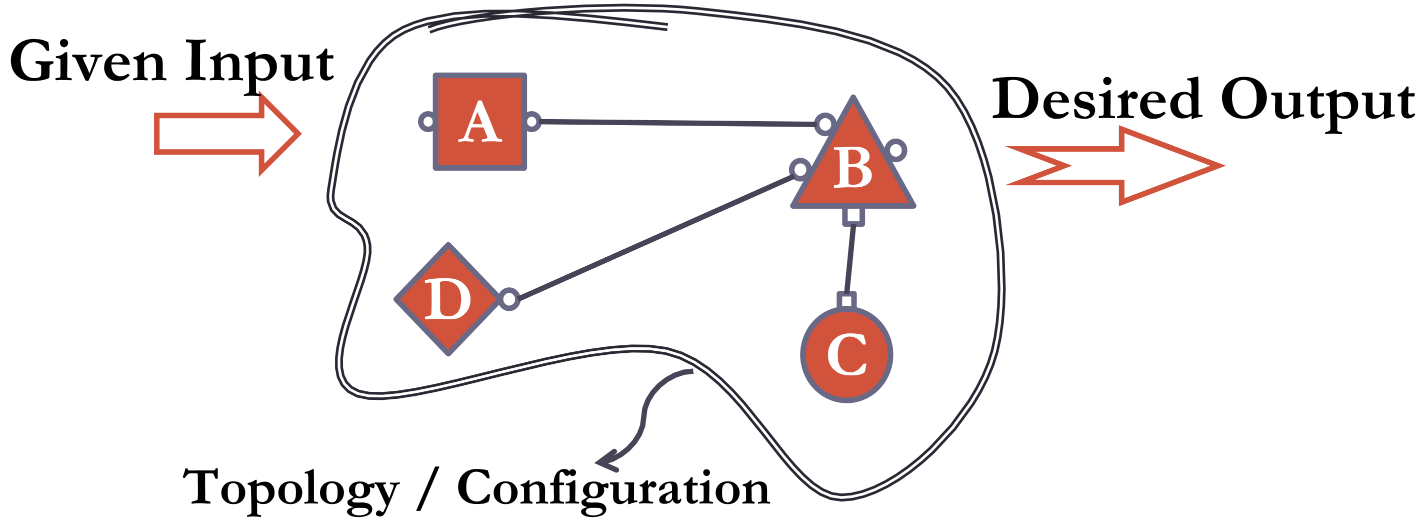
Needs → Concept Generation → Modeling & Optimization → Implementation

My research interests are in general field of
design optimization of complex systems

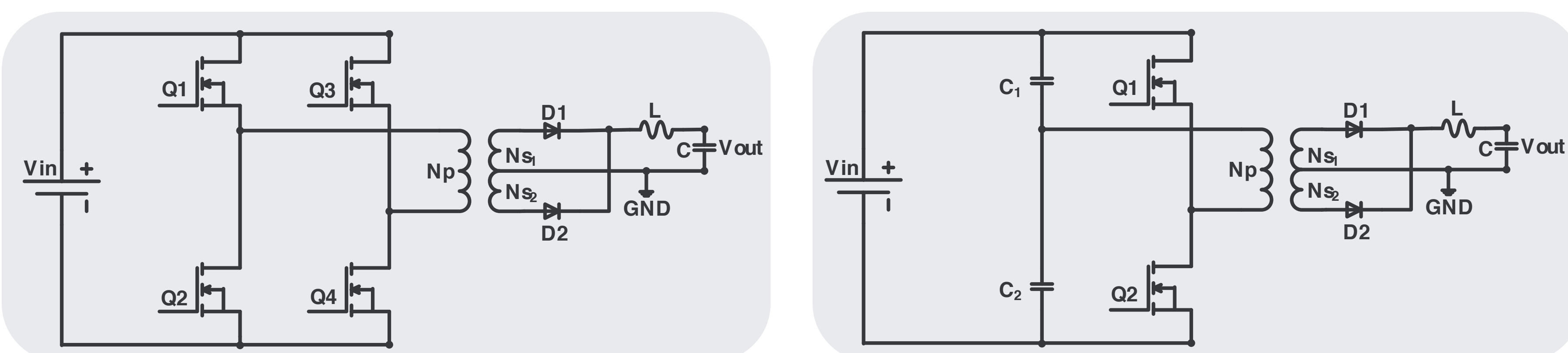
Examples include:

- Smart products that operate with a controller
- Interconnected system of systems

What is a System Architecture?



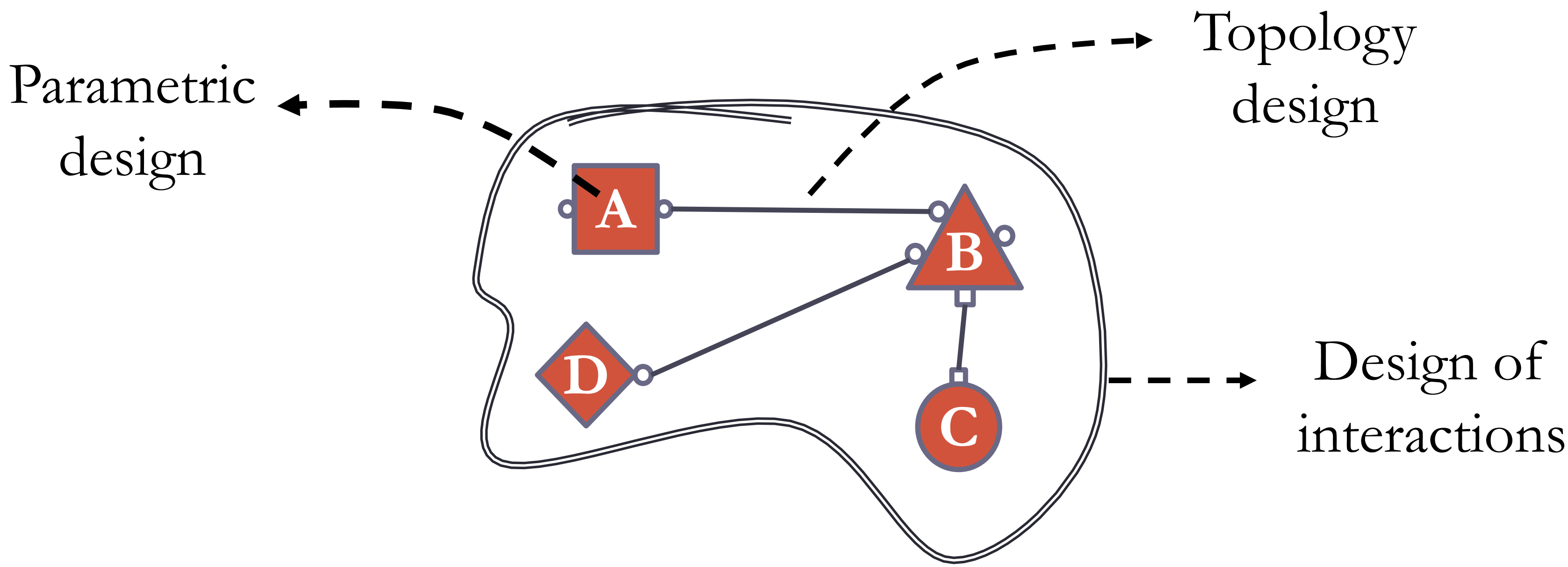
Architecture: Topology + Interactions among building blocks



Multiple alternatives for the same task

System Architecture Design

If the building blocks are known:

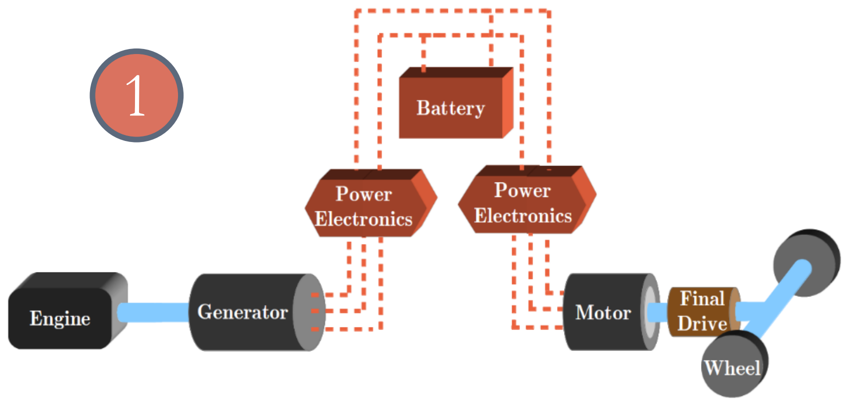


Interactions can be determined by a controller (e.g., smart products) or management strategies (e.g., systems-of-systems, social systems)

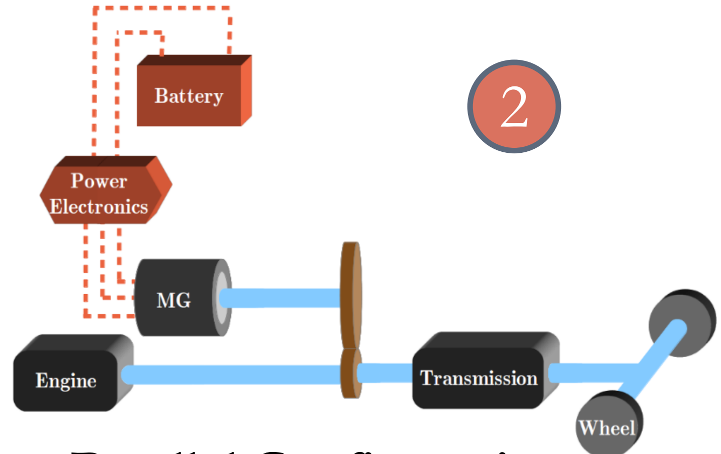
All three design efforts must be combined for successful system operation

Hybrid Electric Powertrain Architecture Design

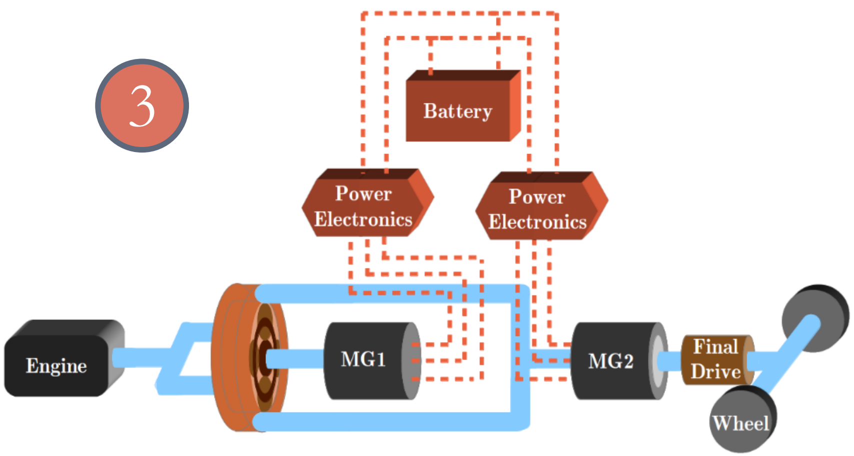
Types of Hybrid Electric Vehicle Configurations



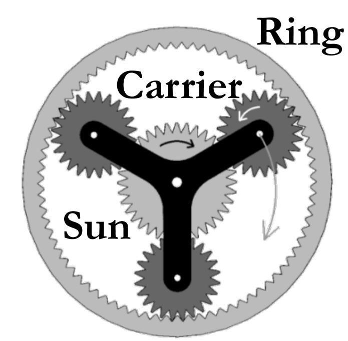
Series Configuration



Parallel Configuration

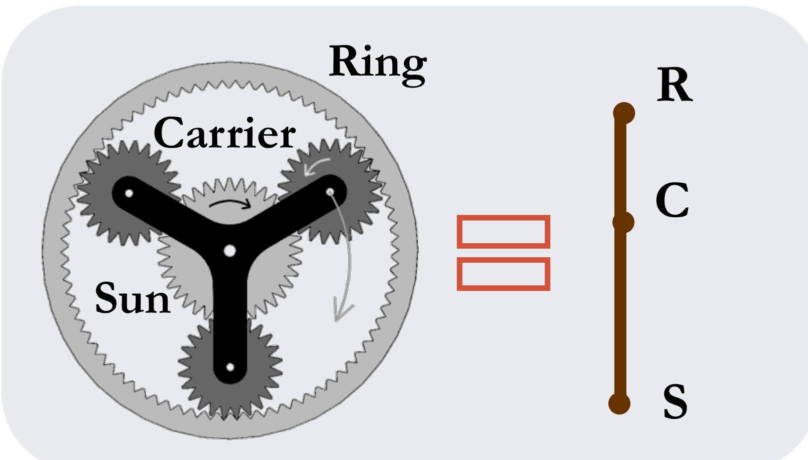


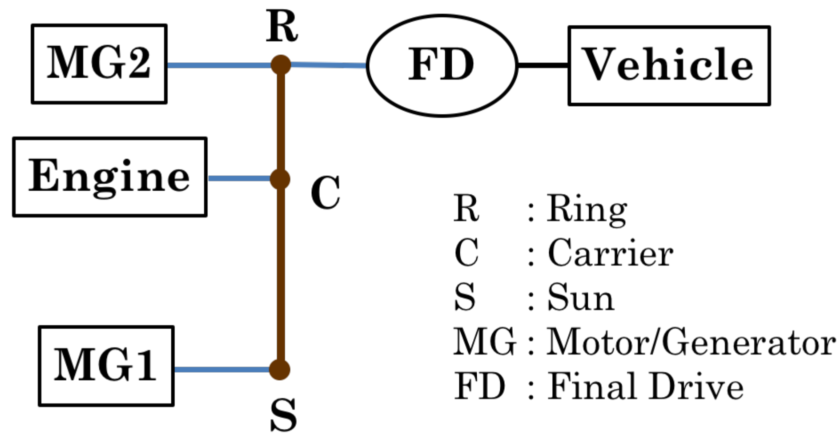
Power-split Configuration

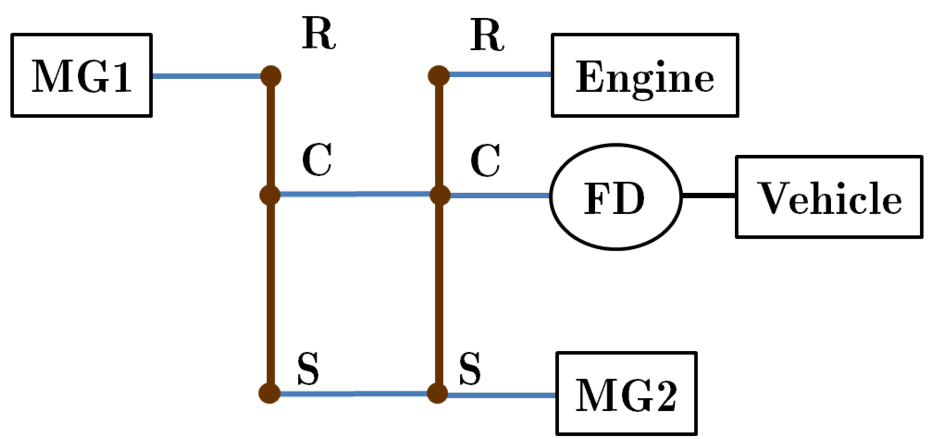


Planetary Gear

Many HEV Configuration Alternatives Possible



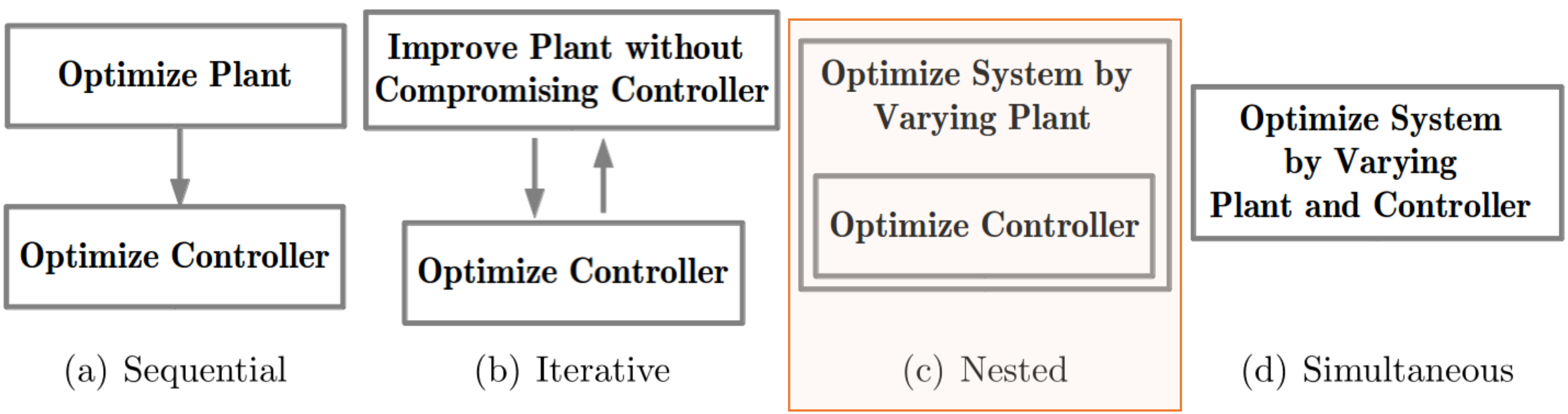




Single-mode configurations

HEV Powertrain Design & Control

- Each design candidate requires a control strategy to evaluate fuel consumption
  - Control: distribute power demand to engine and motors
- Design and control problems are coupled
  - Must be solved together



Fathy et al. (2001)

Problem Overview

Design:

Topology + Component Sizes

Controller

→

maximize:

fuel economy

subject to:

0-60 mph time $\leq k_1$

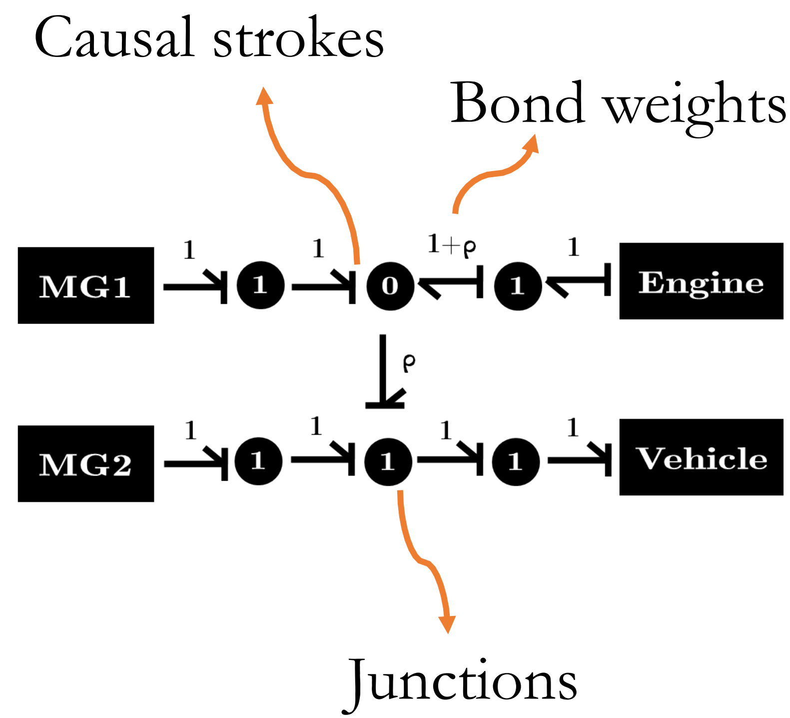
Top speed $\geq k_2$

Architecture alternatives are usually unknown

→ Representation → Generation → Design

Representation & Generation

Bond Graphs

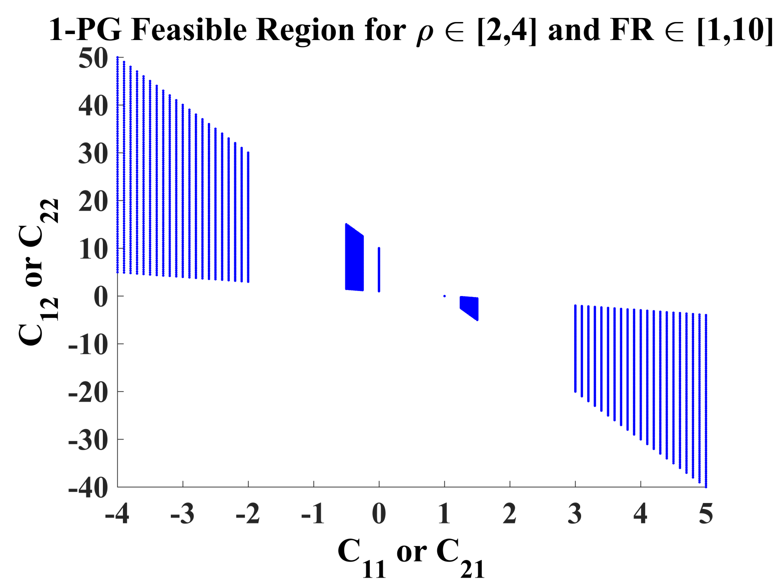


ρ: Gear ratio

FR: Final drive ratio

Quasi-static equations extracted from bond graphs

$$\underbrace{\begin{bmatrix}1+\rho & -\rho\cdot FR\\ 0 & FR\end{bmatrix}}_{\mathbf{C}_{conf}}\begin{bmatrix}\omega_{eng}\\ \omega_{out}\end{bmatrix} = \begin{bmatrix}\omega_{MG1}\\ \omega_{MG2}\end{bmatrix}$$



Decomposition-based Design Optimization

Design C_{conf}

for Fuel Economy, Performance

→ **High-level design**

Design targets ↓ ↑ Design response

Design topology, ρ, *FR*

to meet targets,

s.t. (Feasibility & Complexity)

→ **Detailed design**

The problem is coordinated using

Analytical Target Cascading (Kim 2001)

Research Direction: Different Applications

- For a real-life implementation, architecture design must consider cost vs benefits

- Current hybrid architecture design research:
  - Flexible architecture design for evolving market
  - Design for heavy duty applications with diverse mission capabilities

- A generalized architecture design methodology for applications beyond vehicles

Design of Modular Architectures for Vehicle Fleets

Modular Approaches

Family of Vehicles

Stryker

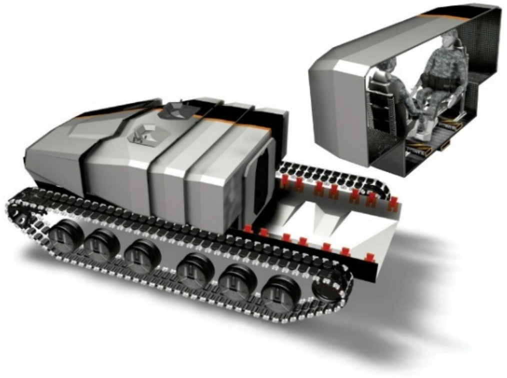
Patria Armored Modular Vehicle

Load Handling Systems

Palletized Load System

Cameleon

Our Approach



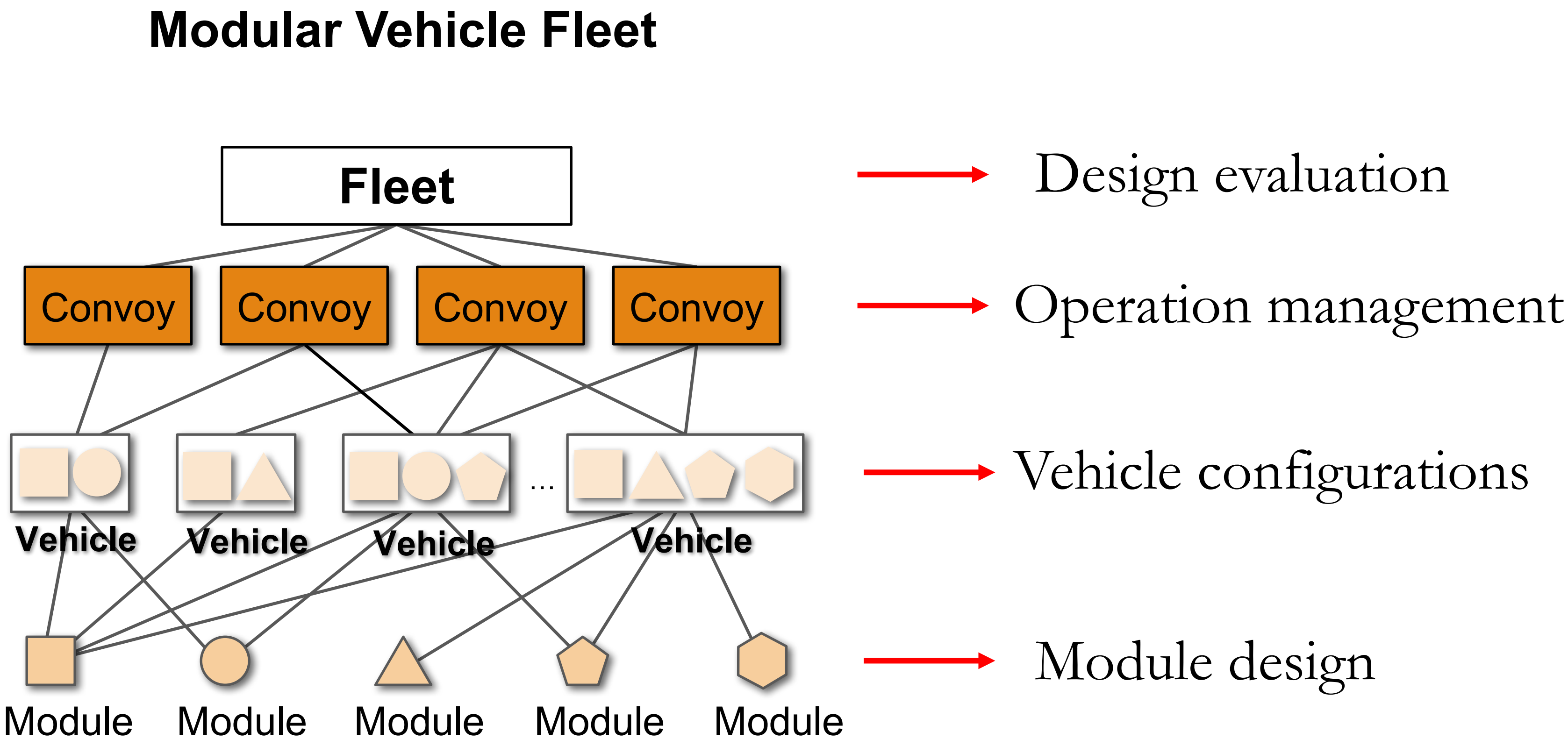
Plug-and-Play Modularity

No common platform

Reconfiguration in theatre

For more details on modularity in practice, see [Dasch, 2015]

Modular Vehicle Fleet Design



Module Design

- What modules enable optimal fleet performance?
- Consider modules as clusters of functions (and enabling variables), therefore question becomes:
  - How should functions/variables be grouped in order to maximize system performance? (**module types**)
  - What should **module variants** be in order to maximize the system performance?

Module Type	**Module Variants**	
Functions: $f_1(v_1, v_2)$, $f_2(v_1)$, $f_3(v_2)$ **Variables: v_1 , v_2**	**Functions: f_1 , f_2 , f_3** **Variables: $v_1=x_{11}$, $v_2=x_{21}$**	**Functions: f_1 , f_2 , f_3** **Variables: $v_1=x_{12}$, $v_2=x_{22}$**

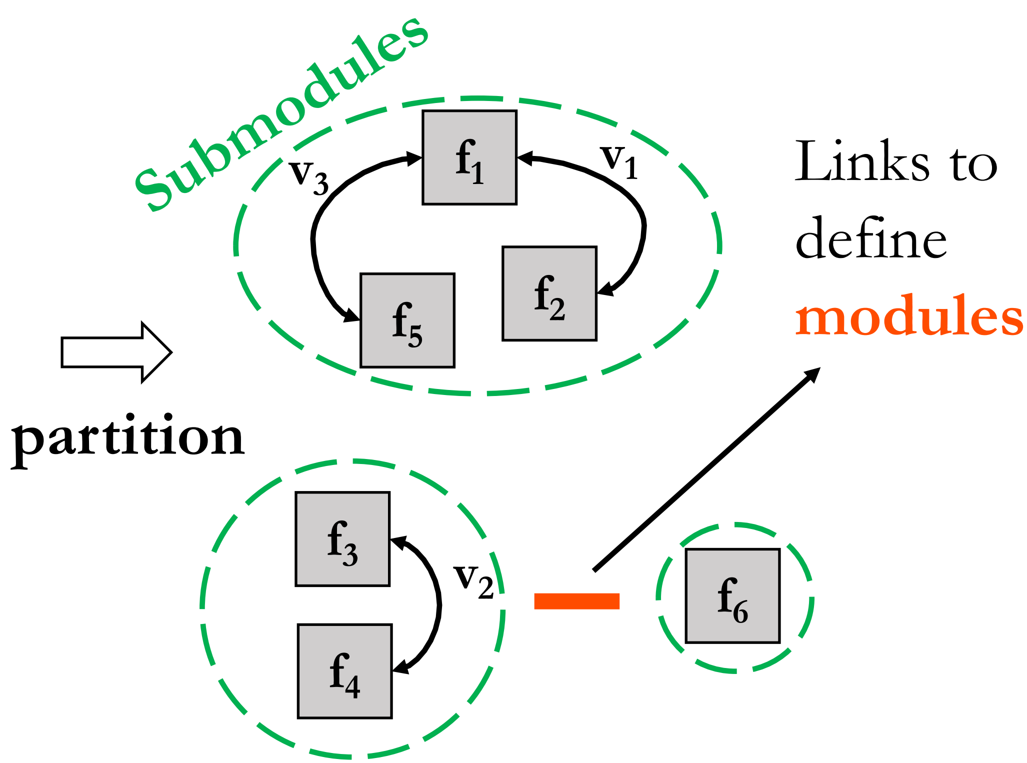
Design of Modules

- Definition of modules impact the effectiveness of the fleet design
- A function-based approach has potential to generate innovative modular concepts

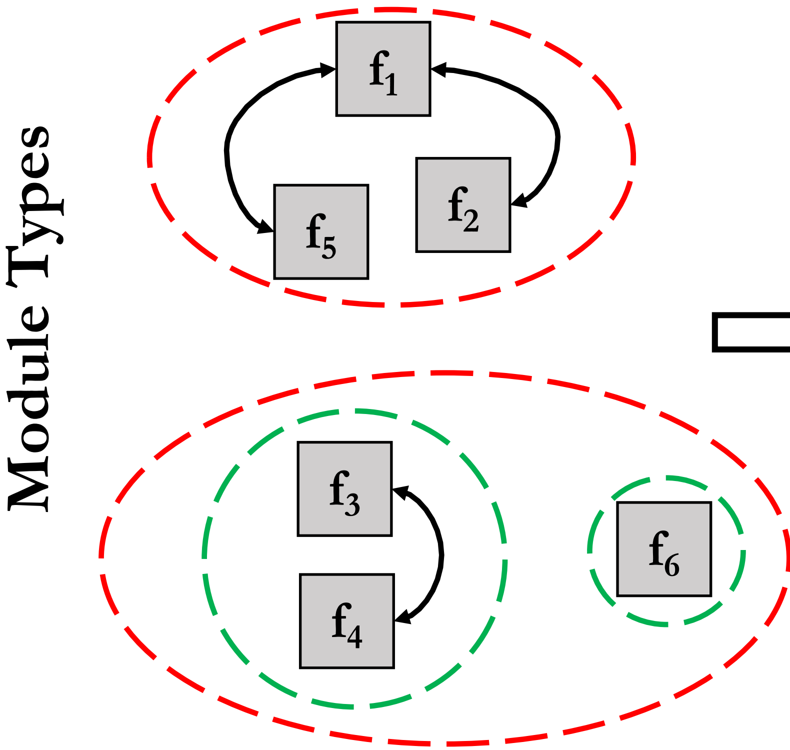
Fleet Decomposition

variables

functions	v_1	v_2	v_3	v_4	v_5
f_1	1		1		
f_2	1			1	
f_3		1			
f_4		1			
f_5			1		
f_6					1



Design of Modules

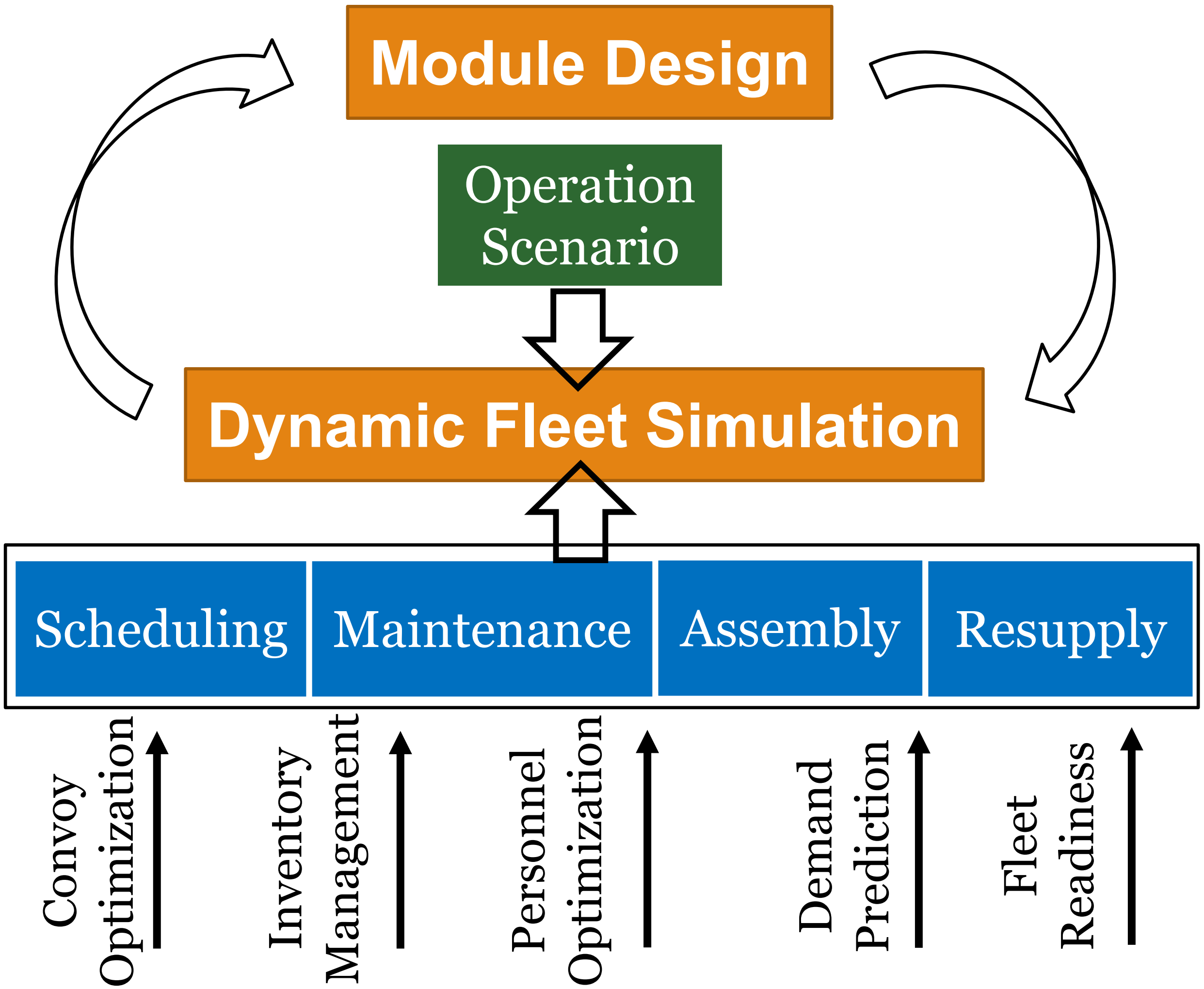


variables / **variants**

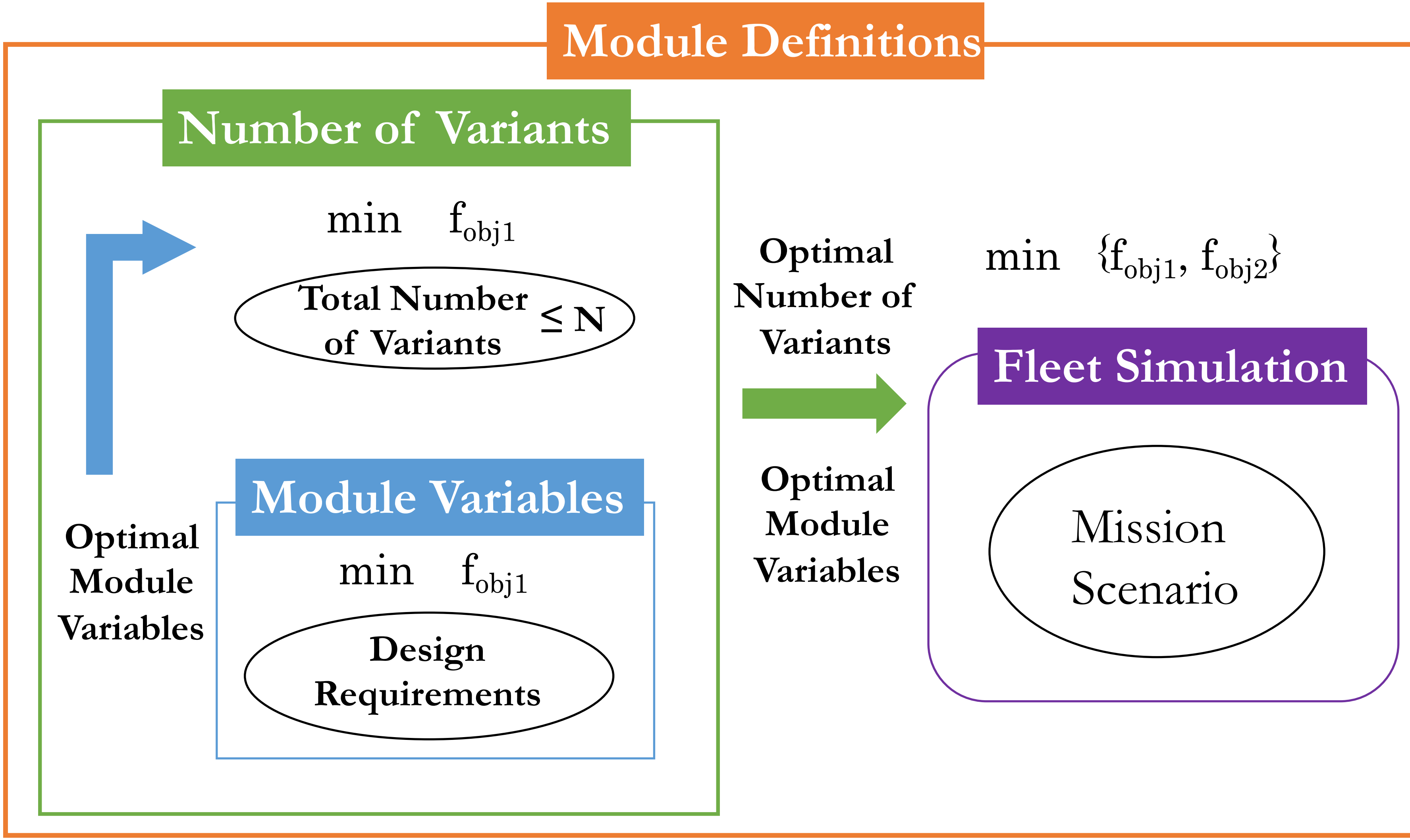
	v_1	v_3	v_4	v_2	v_5
1	x_{11}	x_{31}	x_{41}	x_{21}	x_{51}
2	x_{12}	x_{32}	…	…	…
⋮	…	…	…	…	…
n_2	…	…	…	x_{2n_2}	x_{5n_2}
⋮	…	…	…		
n_1	…	…	x_{4n_1}		

Module design is combined with an operation management in a fleet evaluation framework

Modular Vehicle Fleet Design



Module Design Problem



Design with Game Platforms

Design with Game Platforms

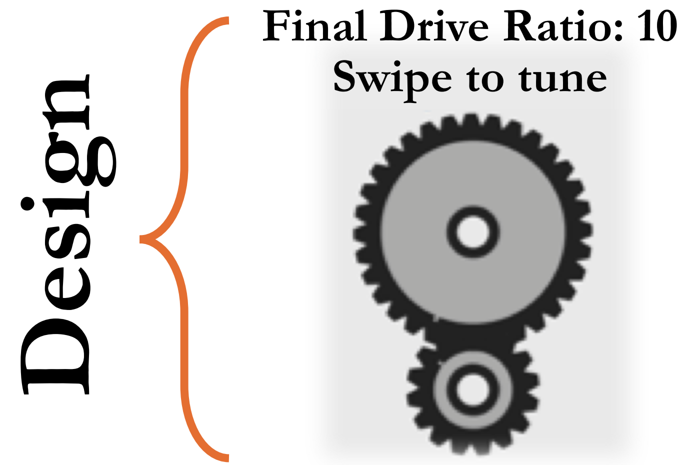
- 42% of Americans play games regularly at least three hours a week (Entertainment Software Association)
- Games are based on excessive trial and error that incentivize a player with fun

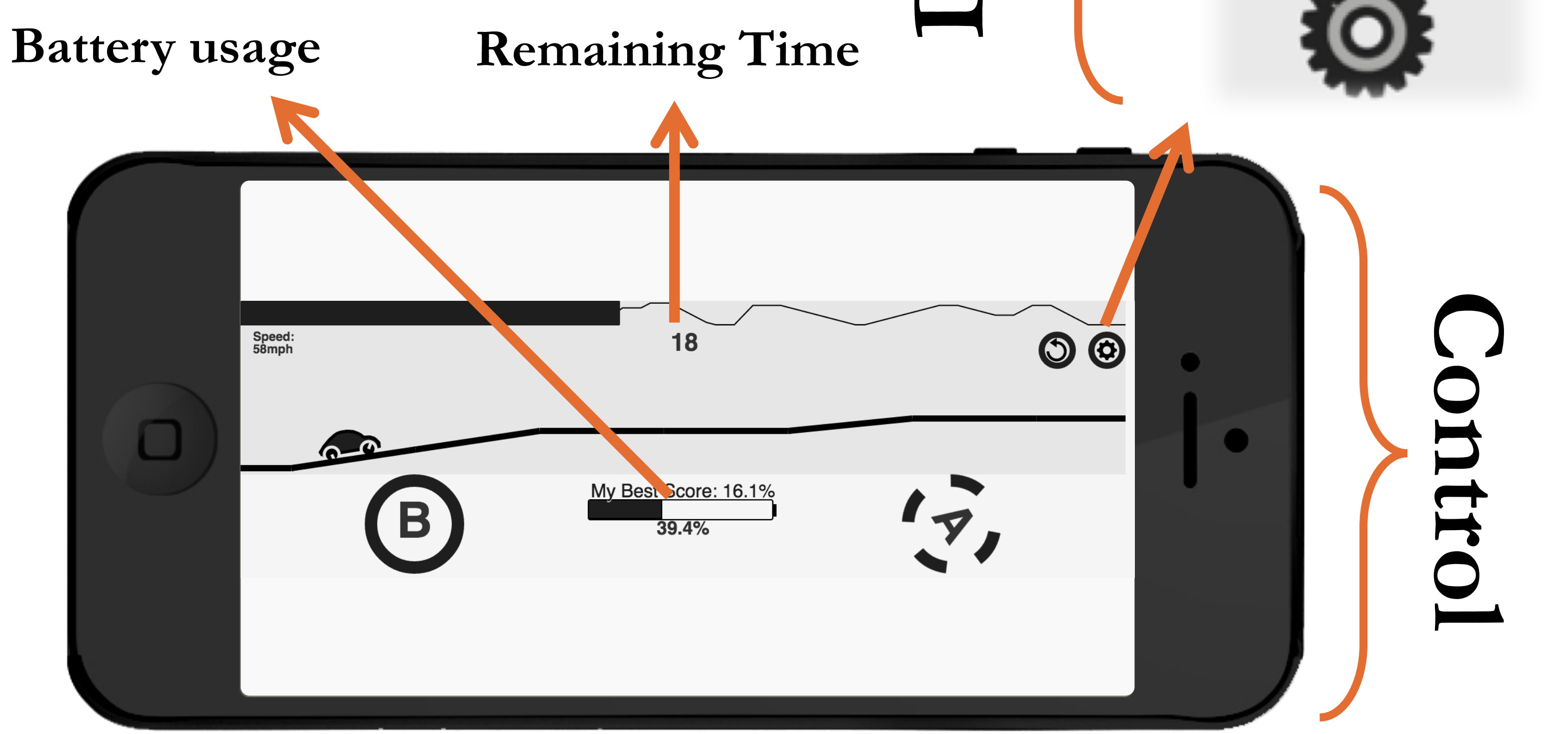
Research on gaming:

1-) Improve gaming experience
2-) Data collection
3-) Problem solving
4-) Education

EcoRacer: EV Design and Control Game

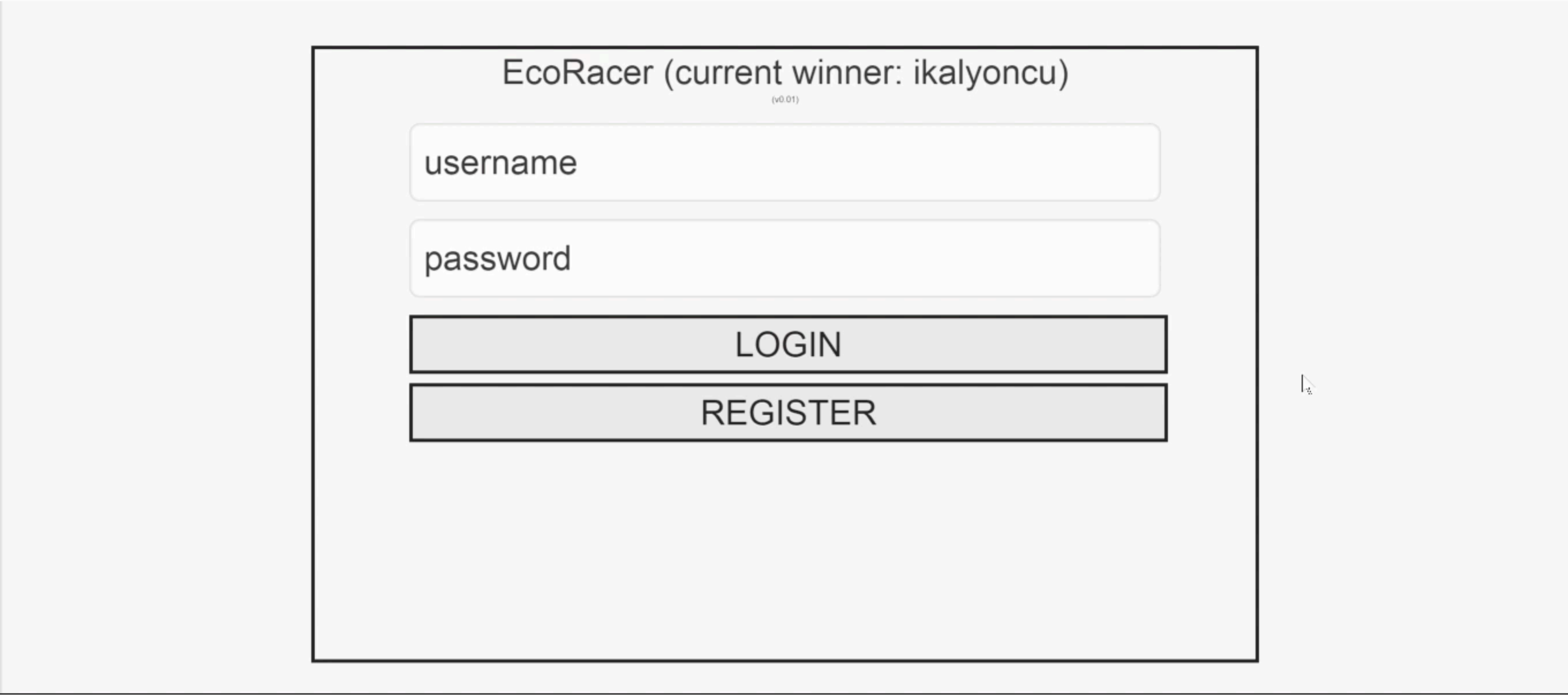
Design the final drive ratio to minimize the battery consumption over a track





Design with Game Platforms

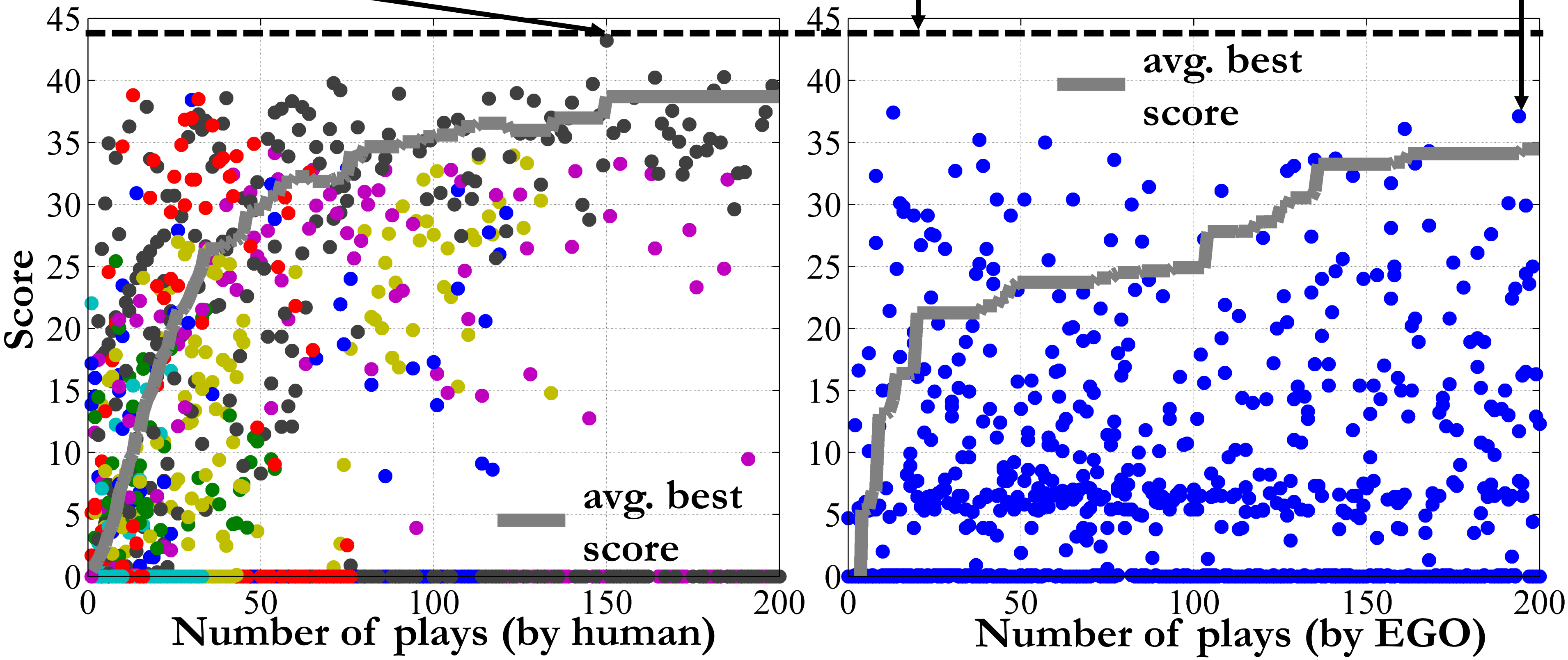
ecoracer.herokuapp.com



Computational Solutions

- Best player score **outperforms** the search algorithm (EGO)
- Using search algorithm is a more **robust approach** than relying on very few experts in the crowd

Best player score: 43.2% (Theoretical upper bound): 43.8% Best EGO score: 37.1%



Research Direction: Urban Planning

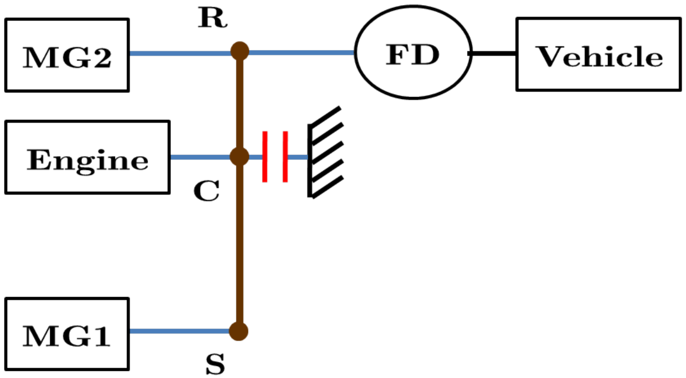
Design Teaching with Game Platforms

- Games can also be used for education.
  - NSF, Gates Foundation, Entertainment Software Association supported this idea
- Current applications include:
  - MIT education arcade (middle-high school biology and math education)
  - Karen Markey (Library search game)
  - Aydogan Ozcan (Maleria training game)…
- In design context, games can be used to teach various trade-offs in a system.
  - Games can guide students for their design project

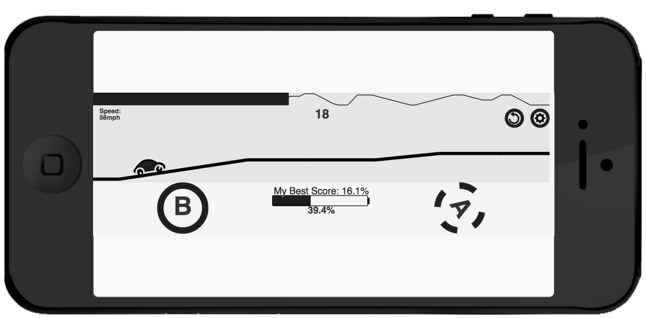
Summary

Integrated System Design Optimization

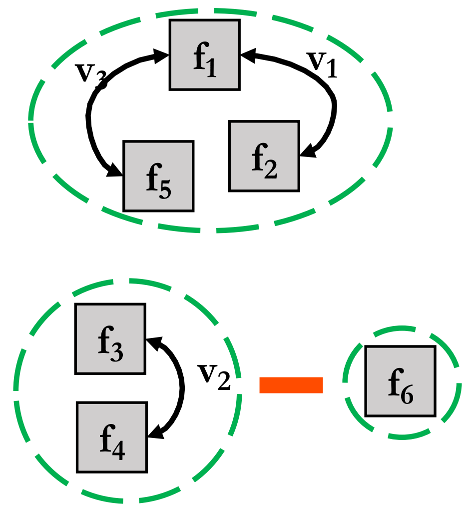
- Powertrain Architecture Design



- Design with Game Platform



- Modular System Design



Thanks!

What questions do you have?