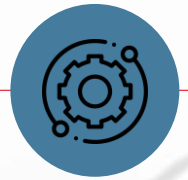
OPTIMIZATION-BASED PARAMETRIC DESIGN VIA HIGH-FIDELITY SIMULATION: OVERVIEW + EXAMPLES

Alexander Schepelmann, Ph.D.
NASA Glenn Research Center, Cleveland, OH 44135



Thermal & Fluids Analysis Workshop, Cleveland, Ohio
August 28, 2024

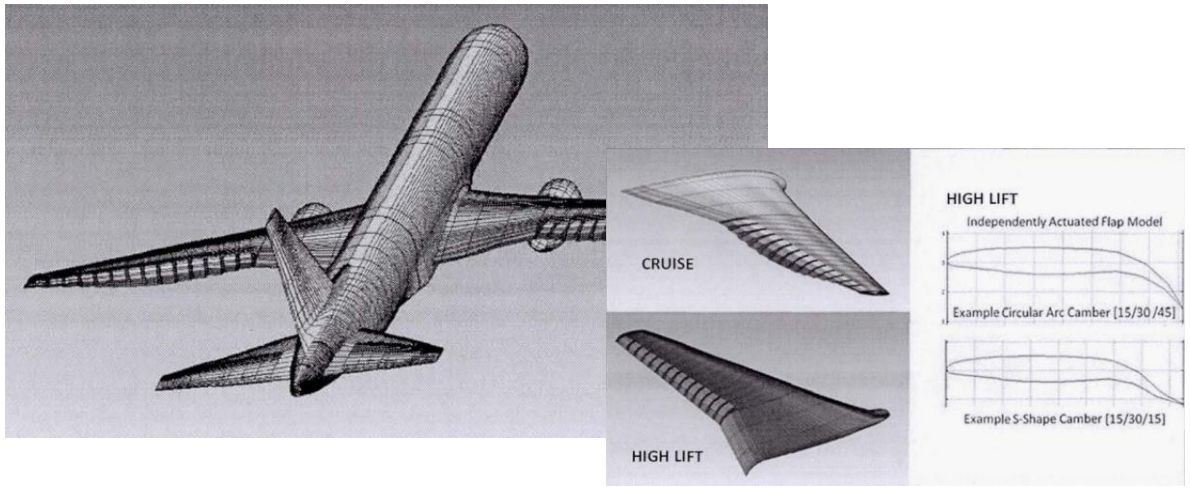
THE DESIGN-BUILD-TEST (DBT) APPROACH IS FLAWED

- Lengthy hardware development time, high cost
- Limited testing capabilities due to environment differences
- Unoptimized hardware wastes resources

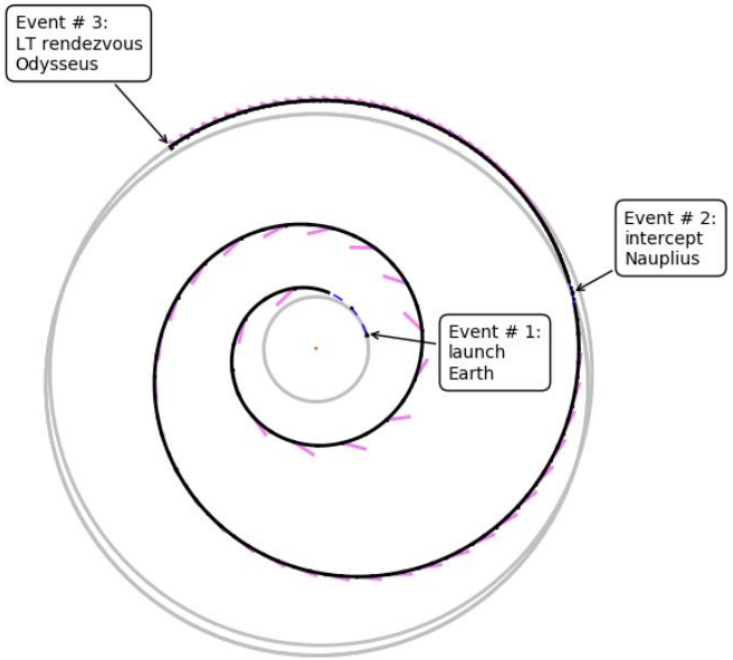
DESIGN CAN (AND SHOULD!) BE LARGELY AUTOMATED

Optimization-based design with **physical simulation** can reduce the time, effort, and cost required to develop and deploy hardware that is *optimized for its operating environment*.

WHAT IS OPTIMIZATION?



Wing aircraft optimization for improved cruise efficiency [1]

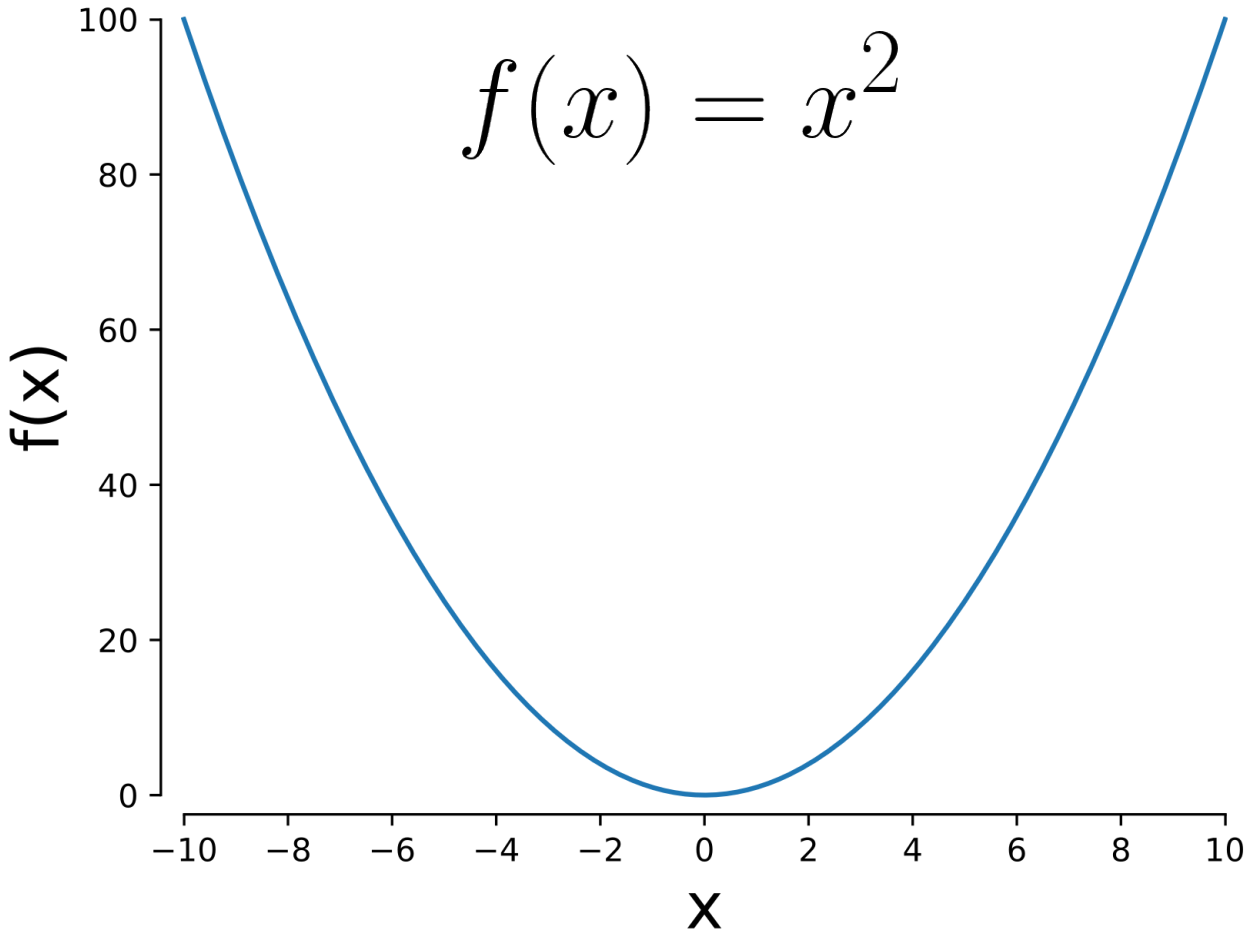


Low-thrust trajectory optimization [2]

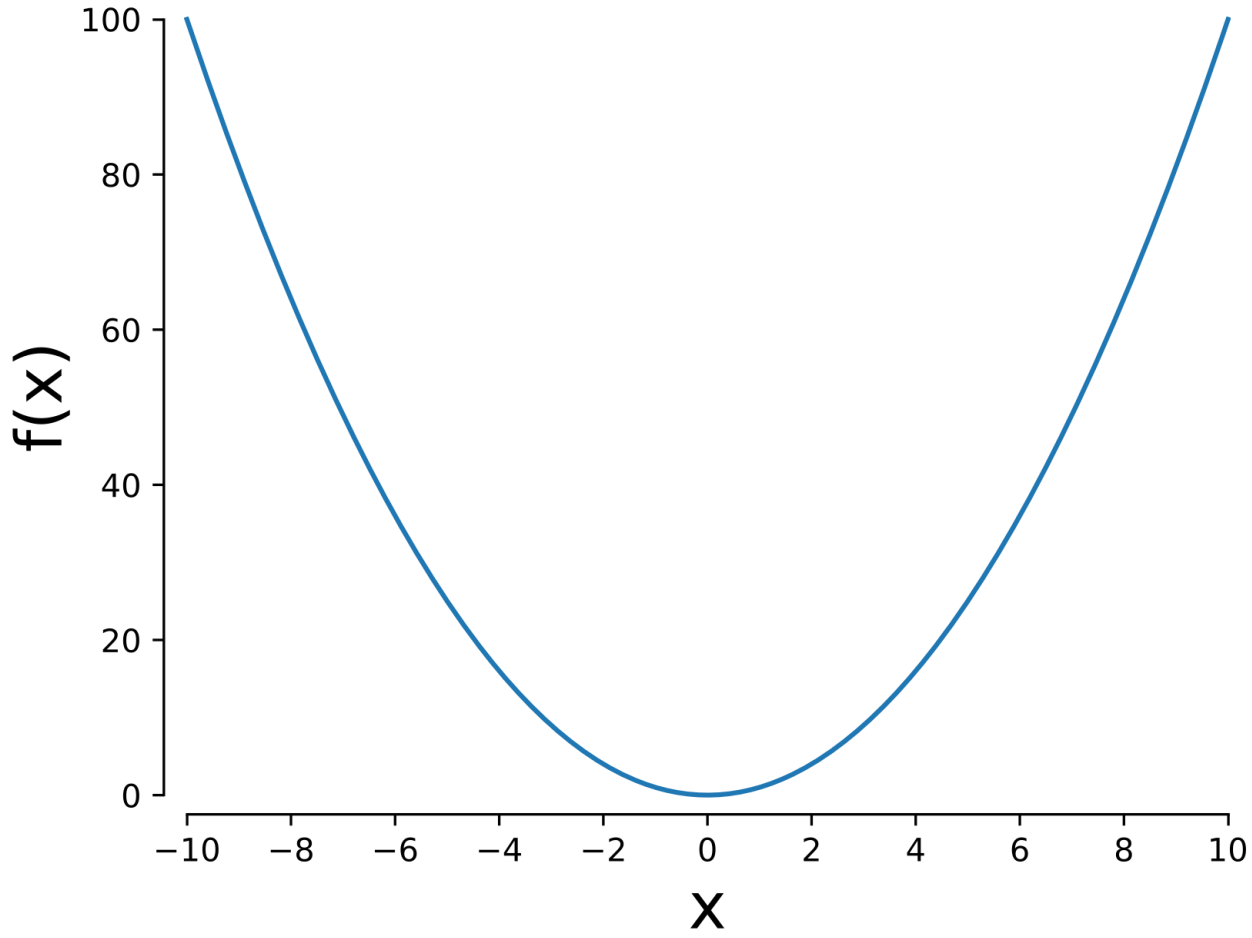
Optimization is the act of **changing input variables** so that **a function is minimized or maximized**.

In optimization-based design, design **"goodness" is expressed mathematically** via a **"cost function."**

WHAT IS OPTIMIZATION? (CONT'D)

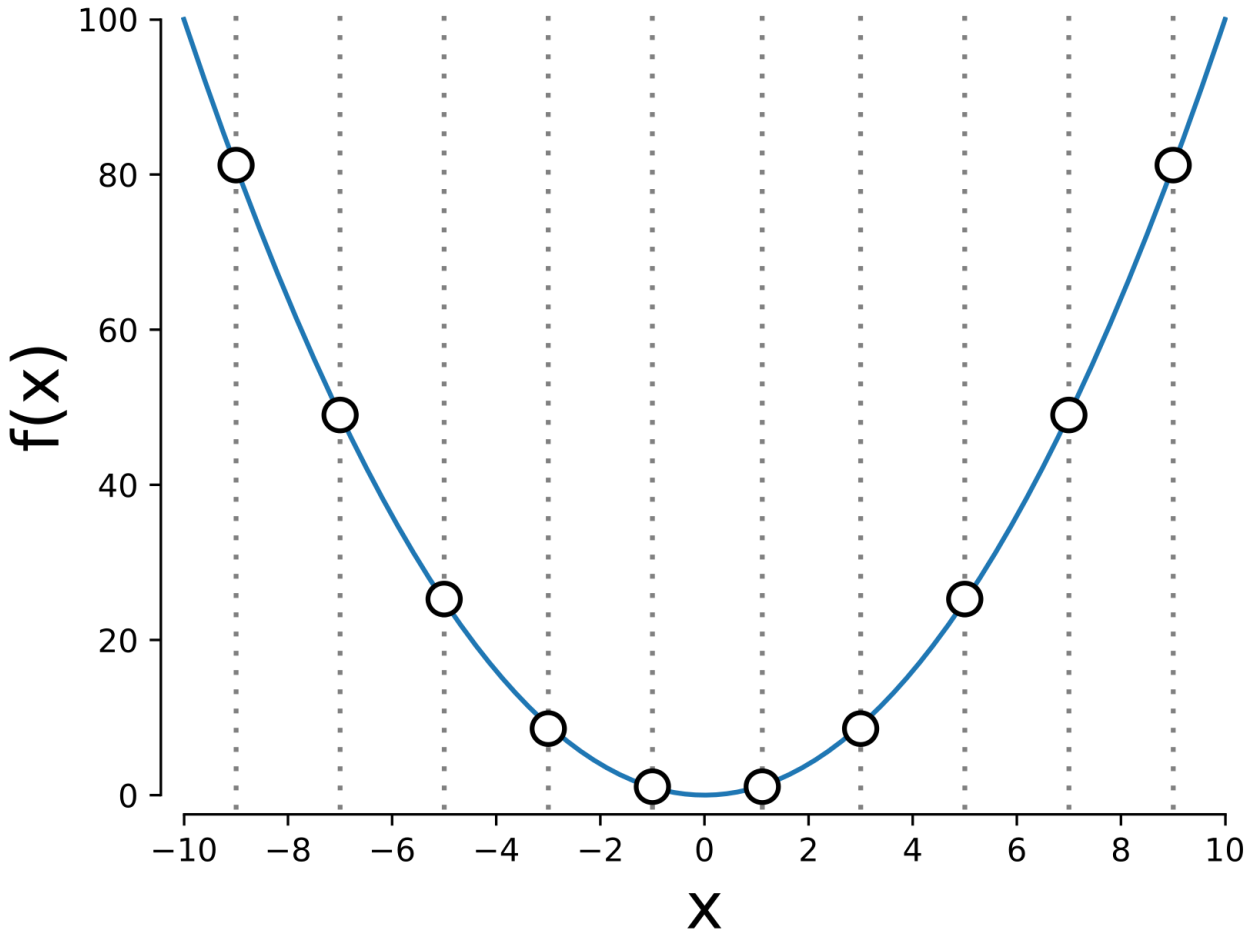


WHAT IS OPTIMIZATION? (CONT'D)



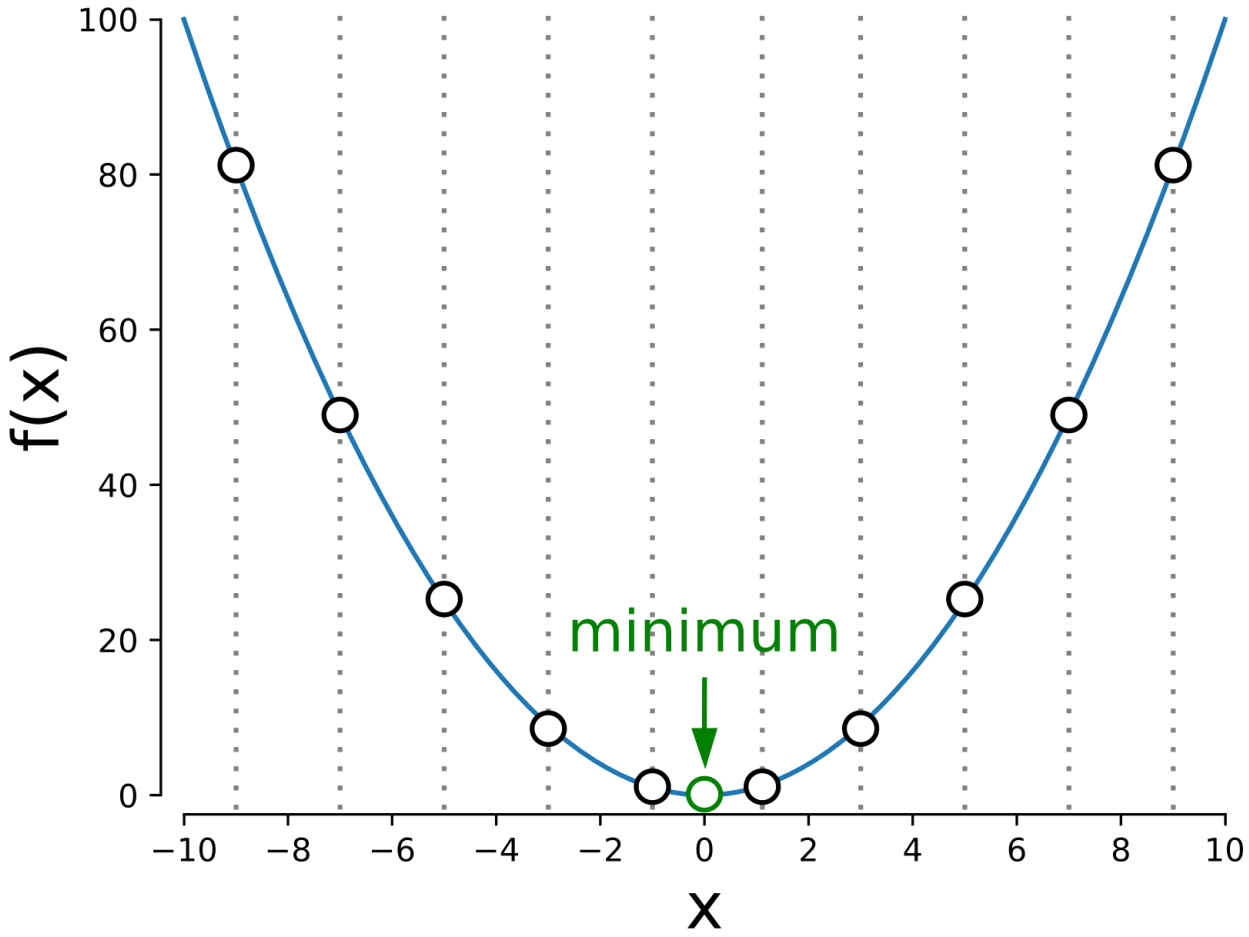
- **Analytically:**
  - $f(x) = x^2$
  - $\frac{d}{dx}(x^2) = 2x$
  - **Min at:** $x = 0$

WHAT IS OPTIMIZATION? (CONT'D)



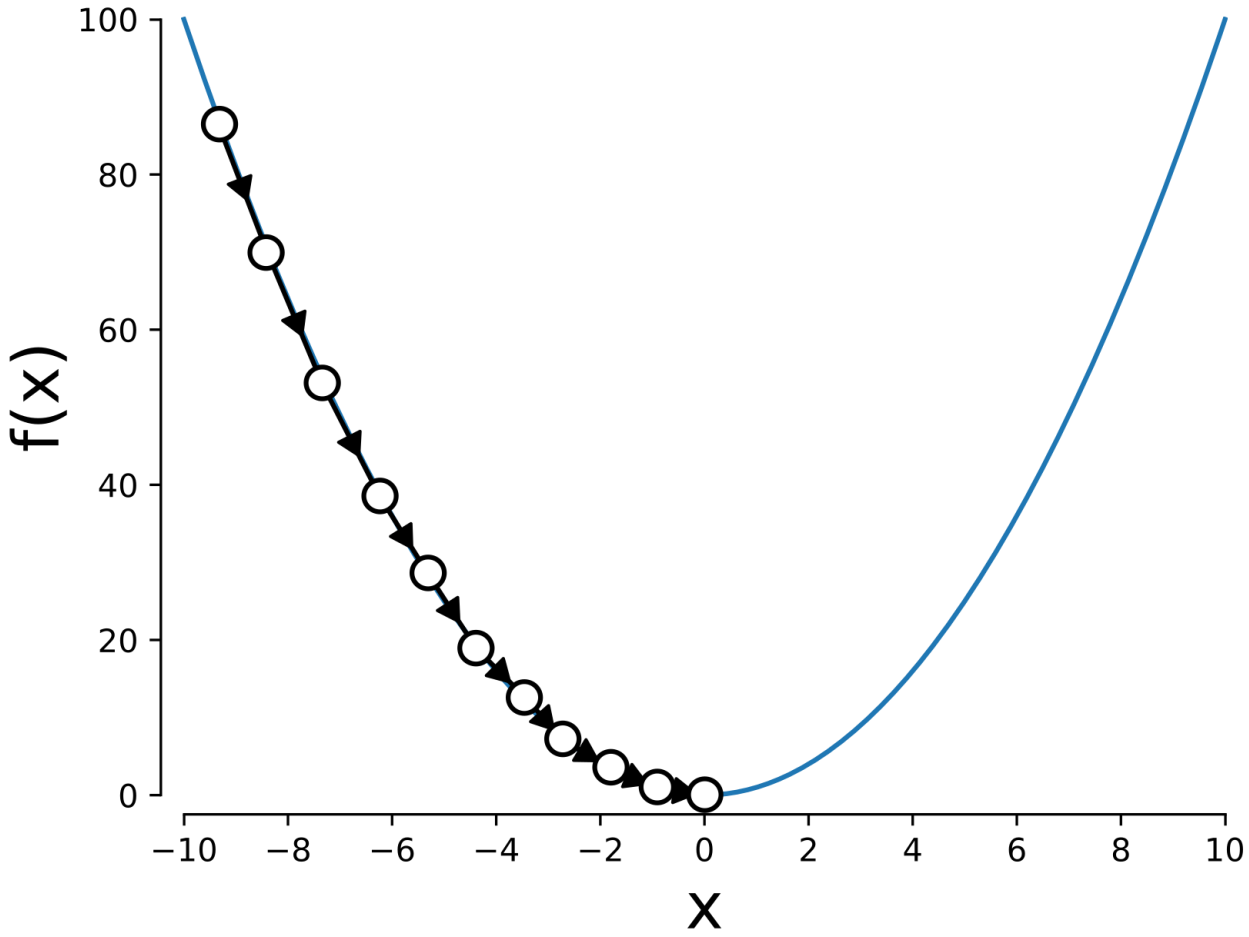
- **Discretization**

WHAT IS OPTIMIZATION? (CONT'D)



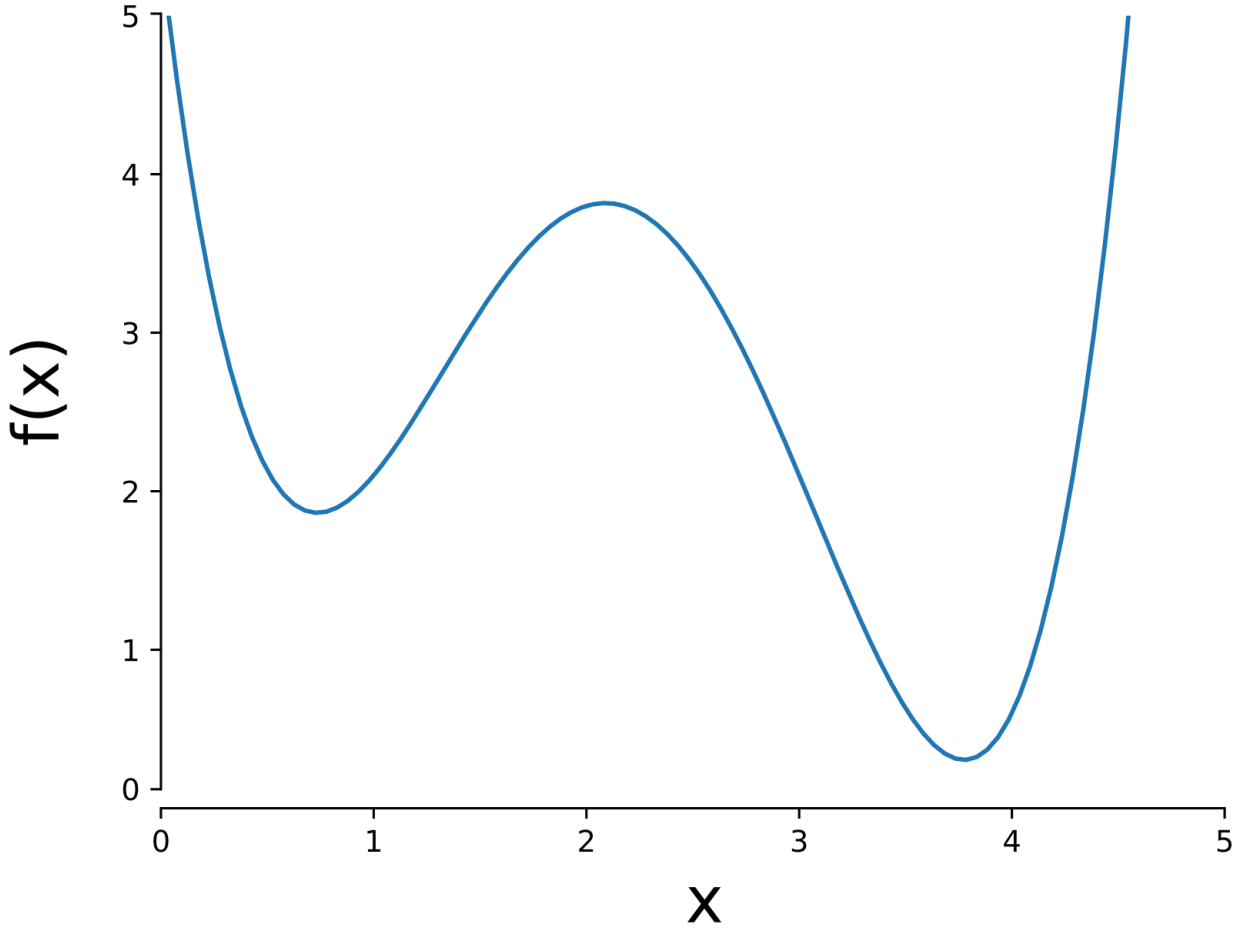
- **Discretization:**
  - Only close to minimum
  - Computationally expensive

WHAT IS OPTIMIZATION? (CONT'D)



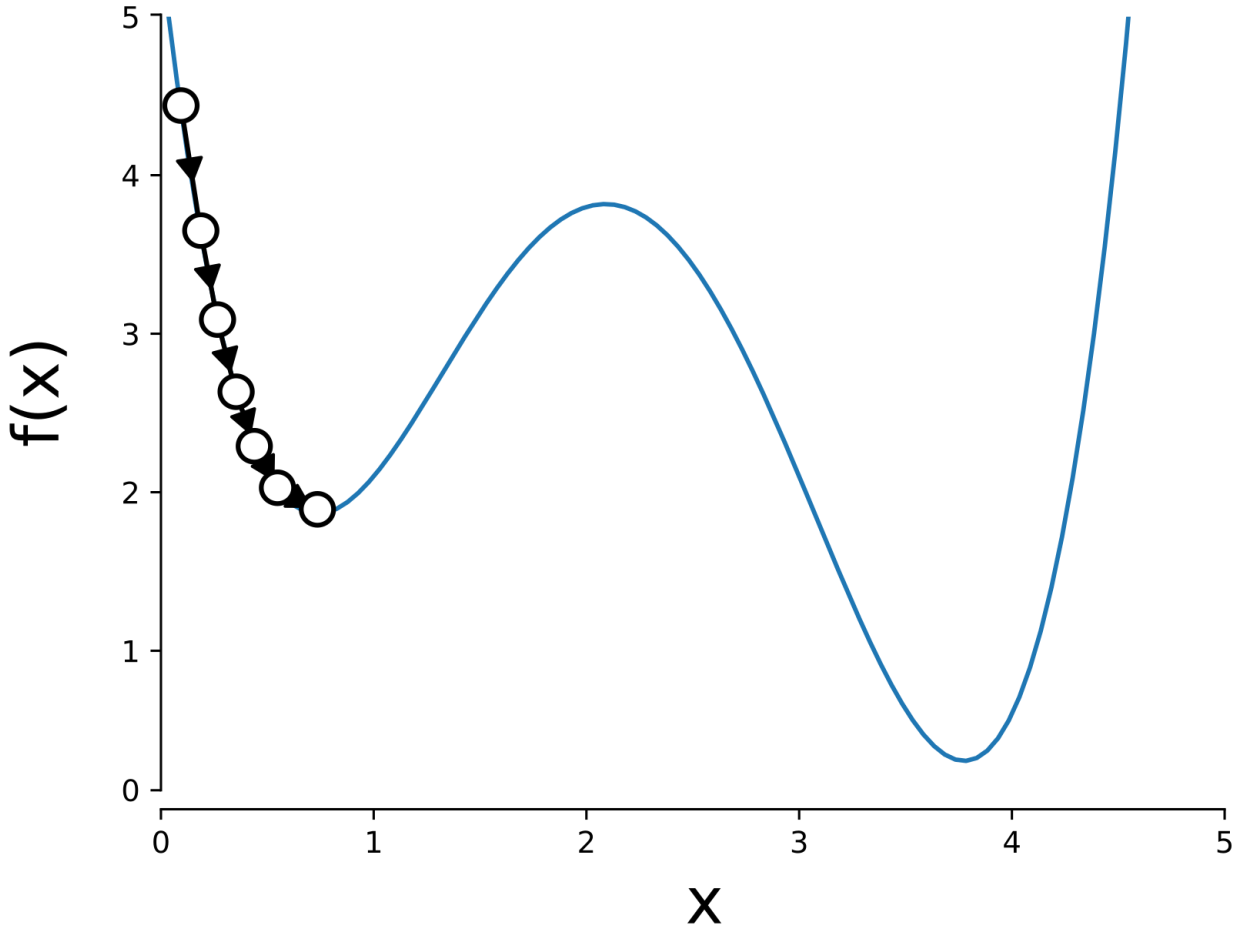
- **Numerical Approach 1:**
  - *Gradient ascent/descent*
  - $\mathbf{a}_{n+1} = \mathbf{a}_n - \gamma \nabla F(\mathbf{a}_n)$
  - Great for concave/convex problem spaces
  - Computationally efficient vs. discretization

WHAT IS OPTIMIZATION? (CONT'D)



- **What if the problem space isn't convex?**

WHAT IS OPTIMIZATION? (CONT'D)



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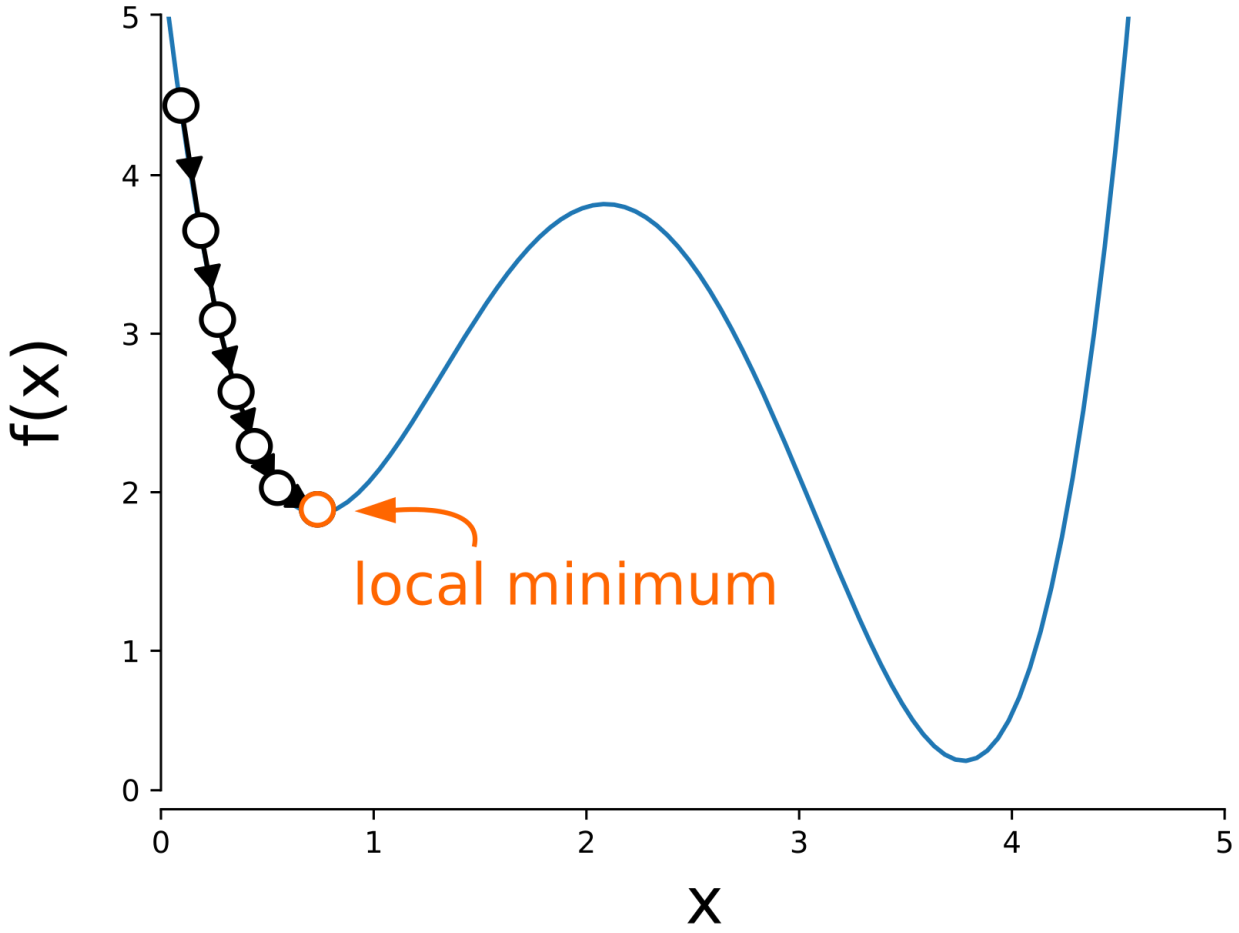

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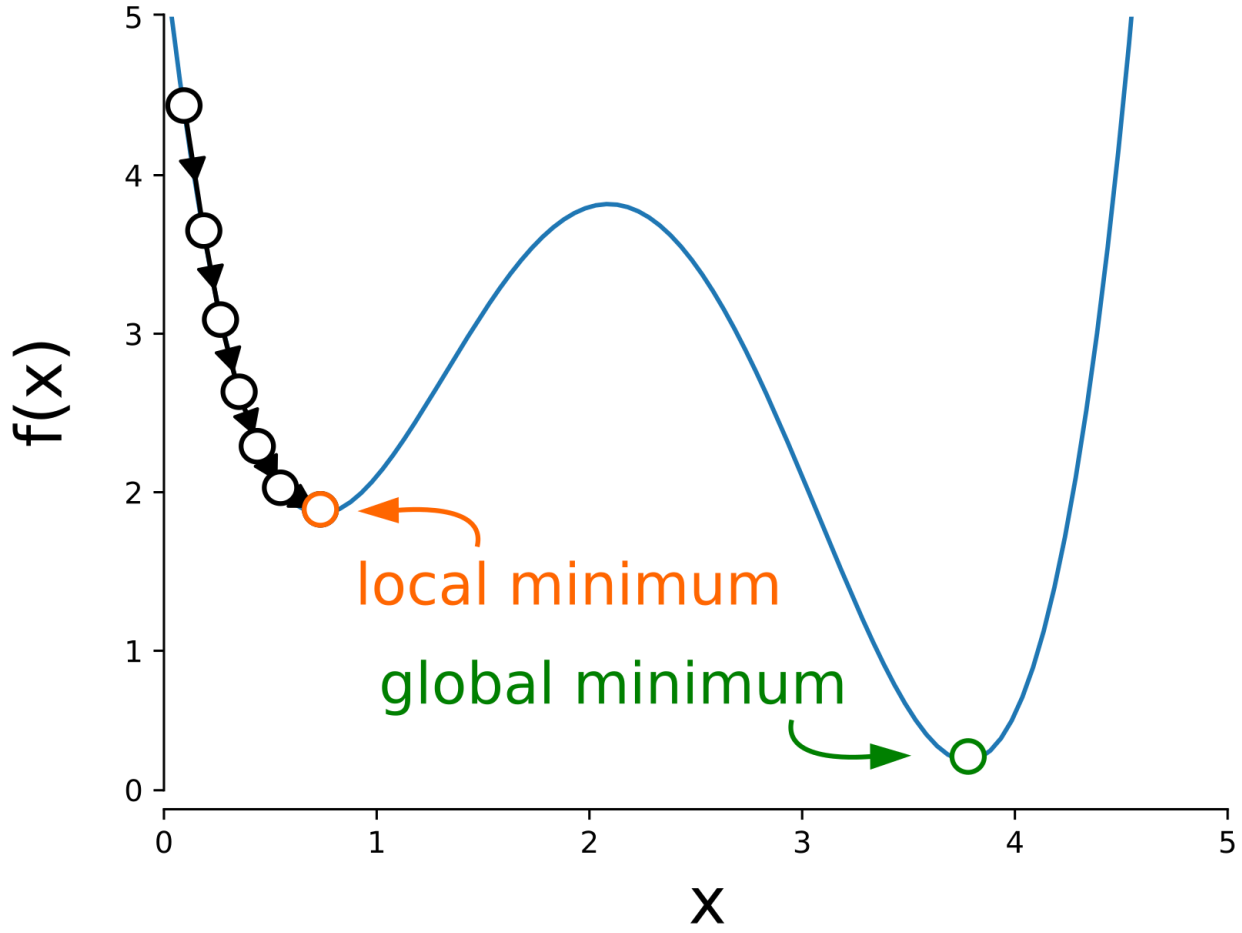
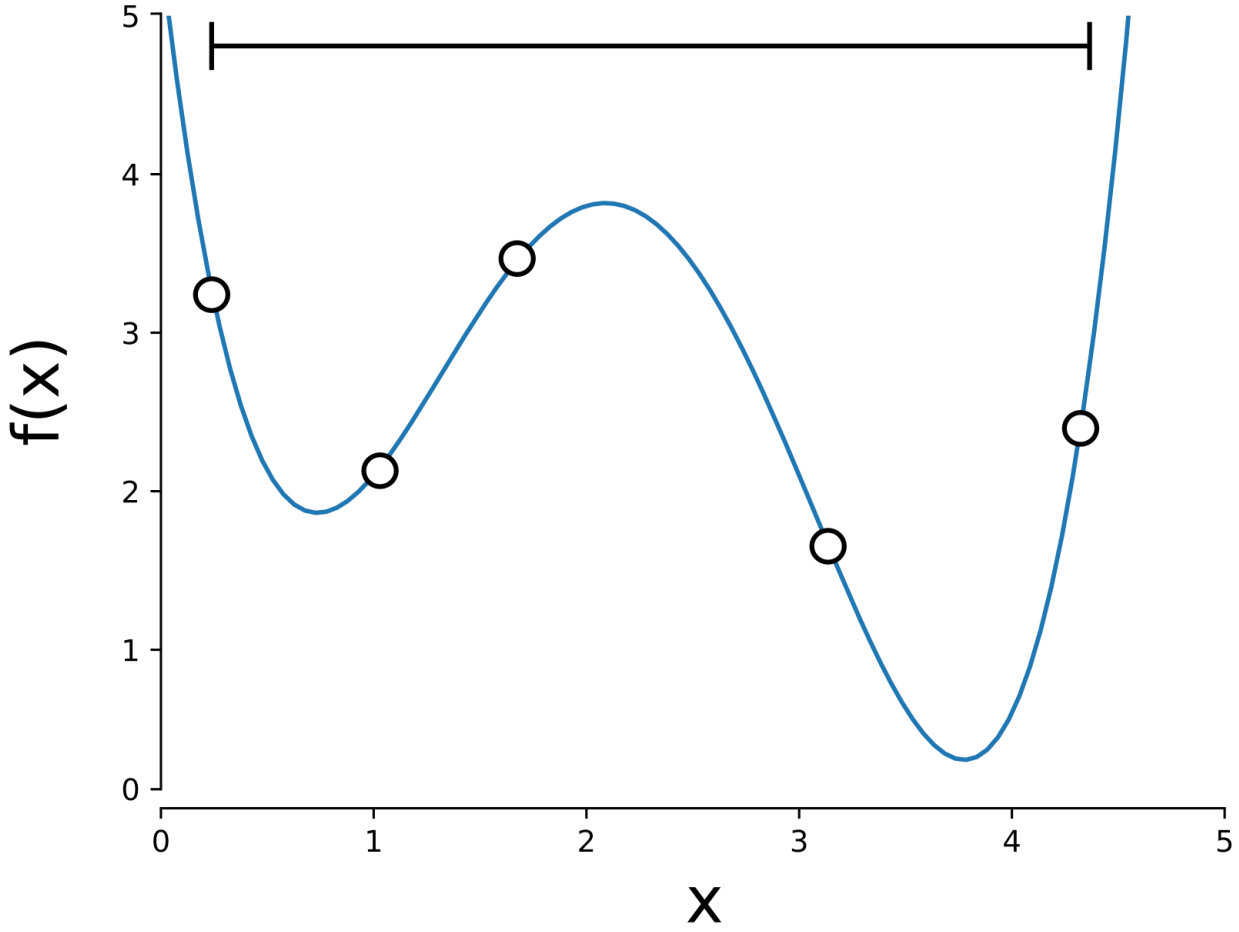


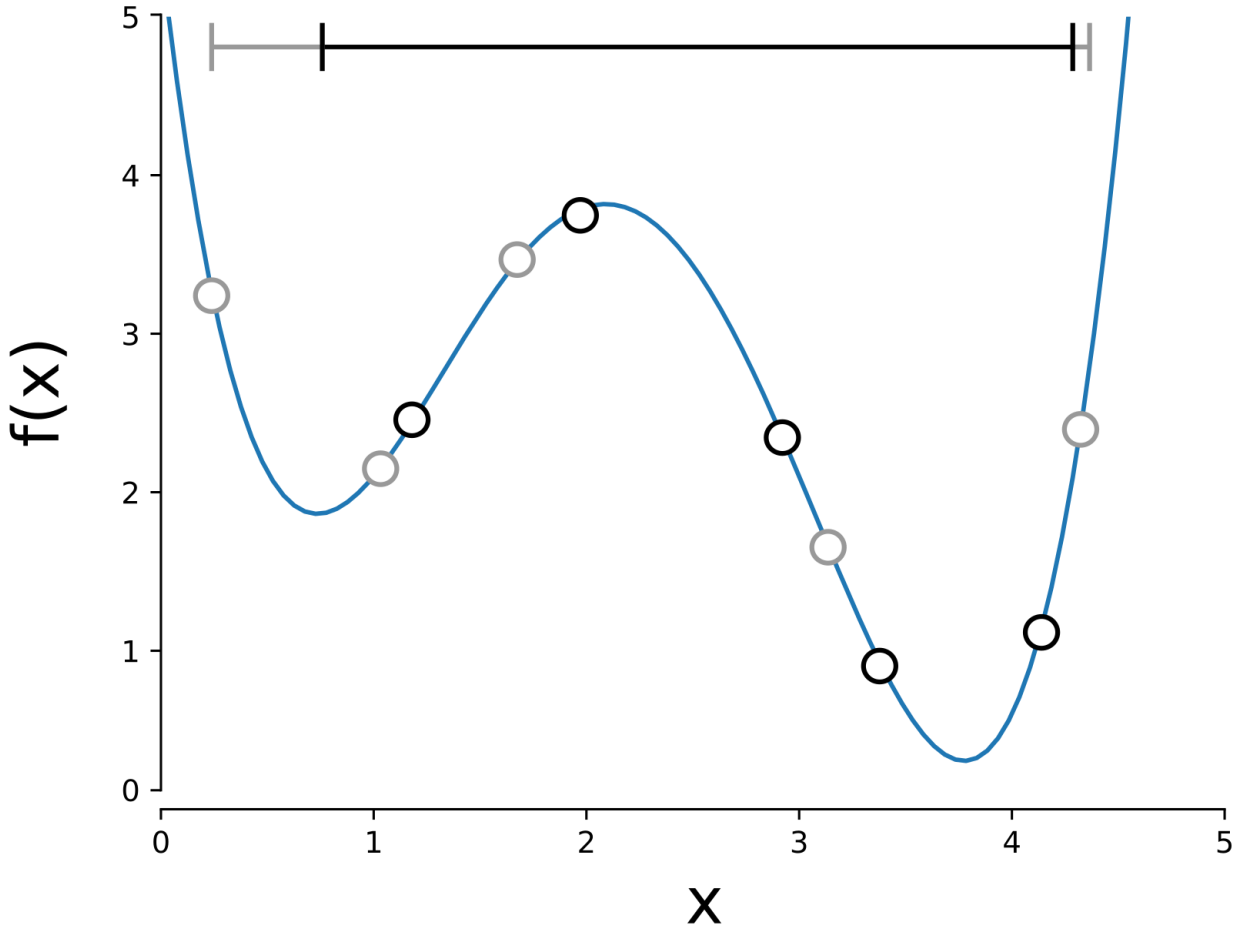
- **What if the problem space isn't convex?**
  - Optimization can converge on local minima

WHAT IS OPTIMIZATION? (CONT'D)



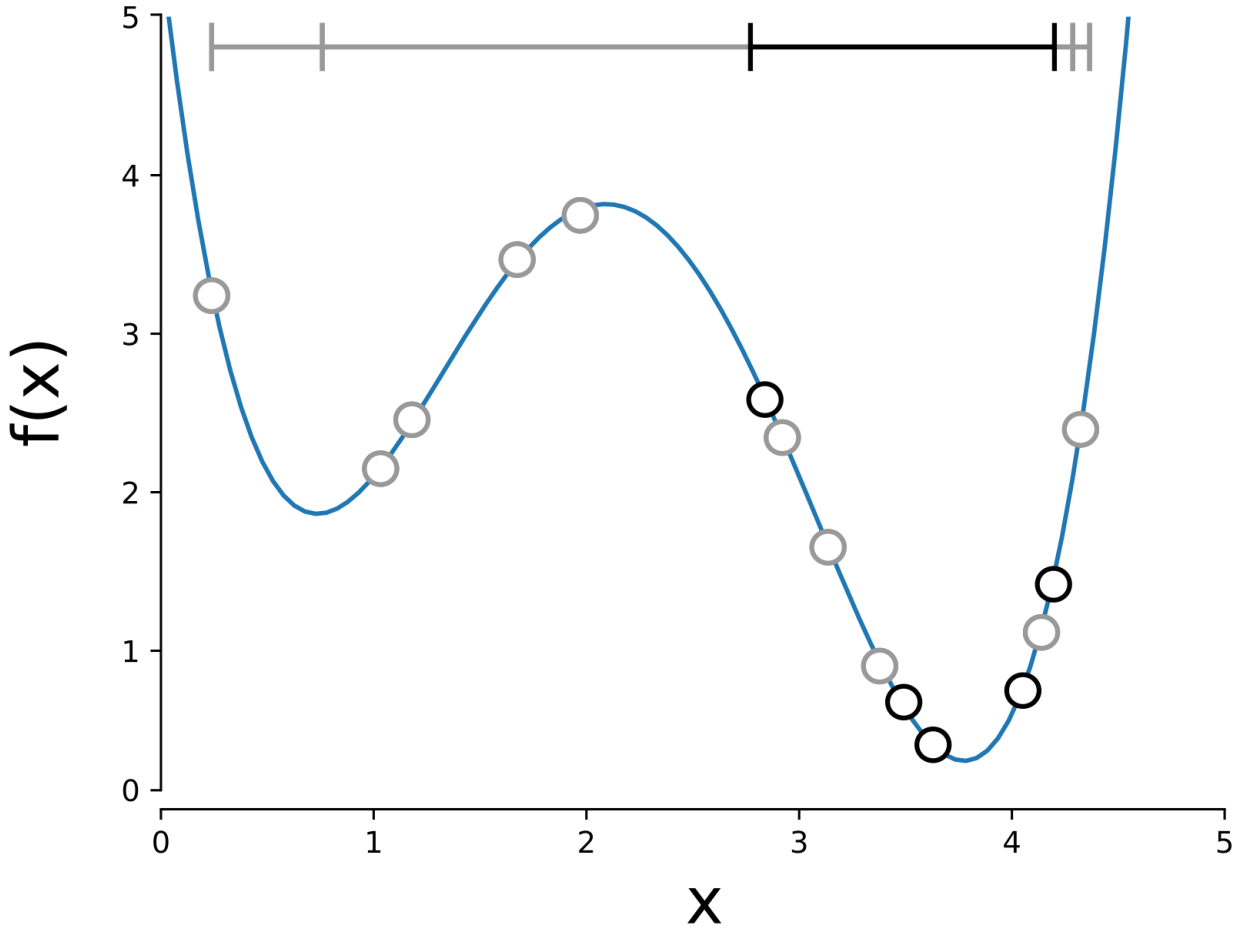
- **Numerical Approach 2:**
  - *Stochastic optimization*

WHAT IS OPTIMIZATION? (CONT'D)



- **Numerical Approach 2:**
  - *Stochastic optimization*
  - Randomly sample input variables within a range, adjusting sample range over multiple iterations

WHAT IS OPTIMIZATION? (CONT'D)



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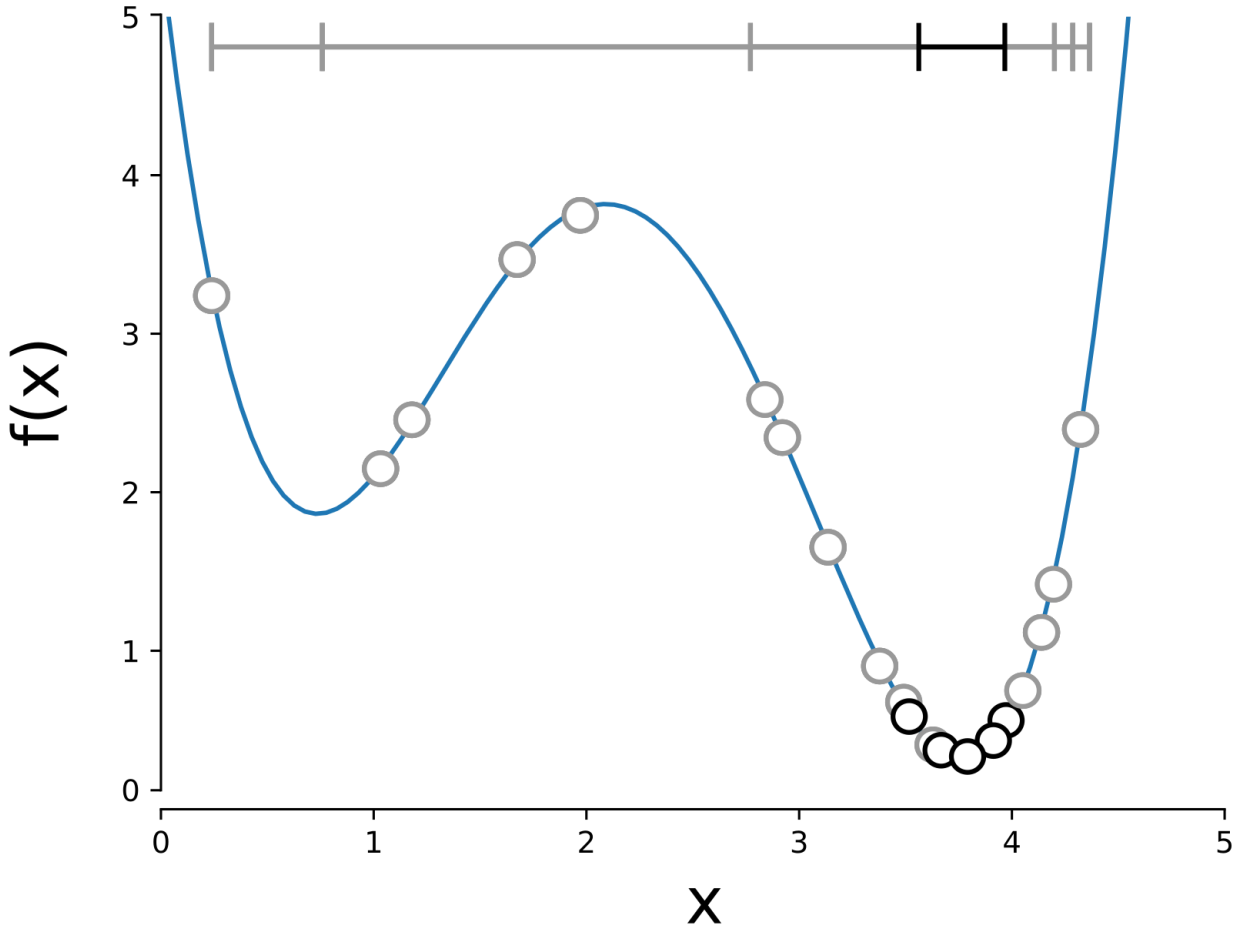

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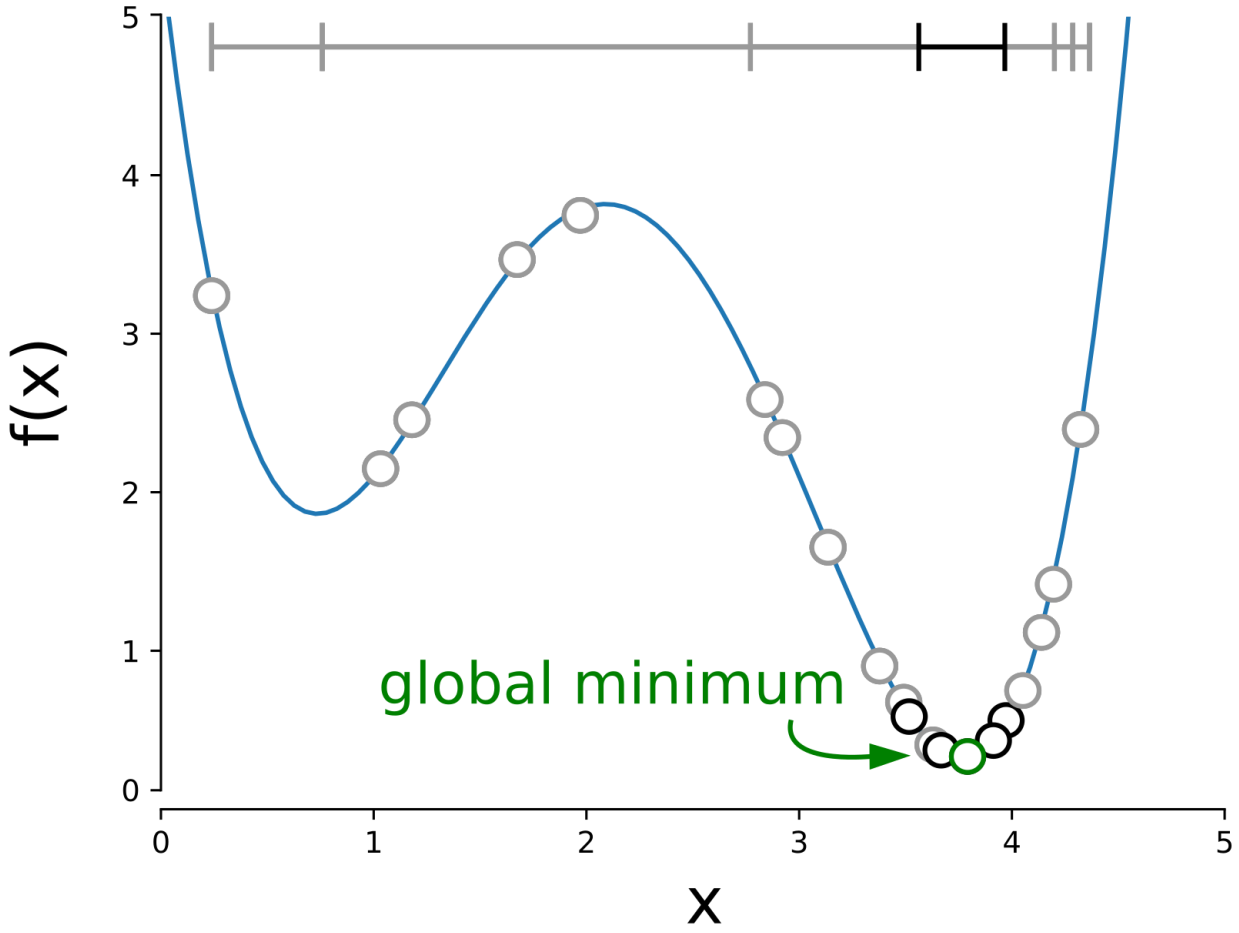
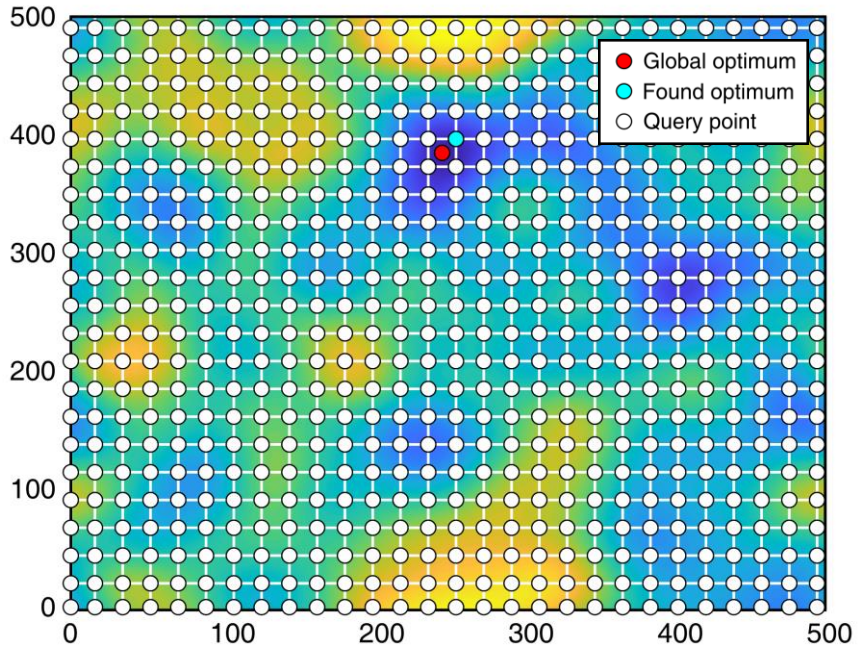


- **Numerical Approach 2:**
  - *Stochastic optimization*
  - Randomly sample input variables within a range, adjusting sample range over multiple iterations
  - Can "escape" local minima
  - Computationally expensive vs. gradient descent

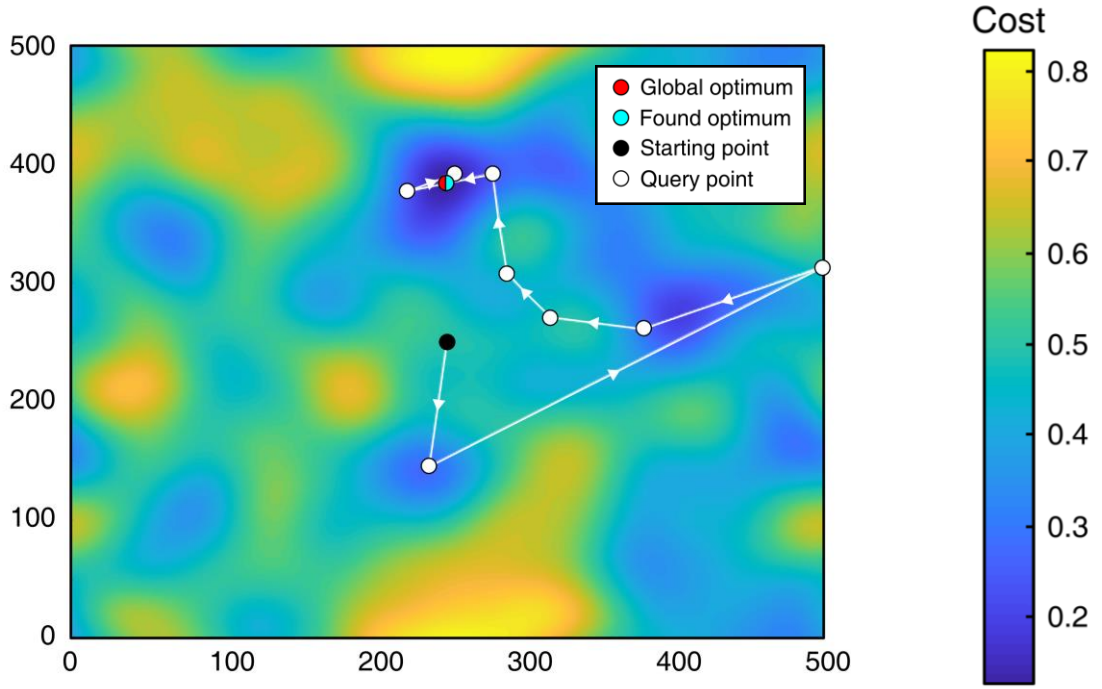
DESIGN OPTIMIZATION IS USUALLY MULTIVARIABLE



$$\arg\min_{n_1,n_2}\{(l_{clr}-l^*_{clr}(x))^2 \mid x = C(n_1,n_2)\}$$

$$n_1 = [n_1^i : \Delta n_1 : n_1^f] \quad n_2 = [n_2^i : \Delta n_2 : n_2^f]$$

2D parameter space discretization



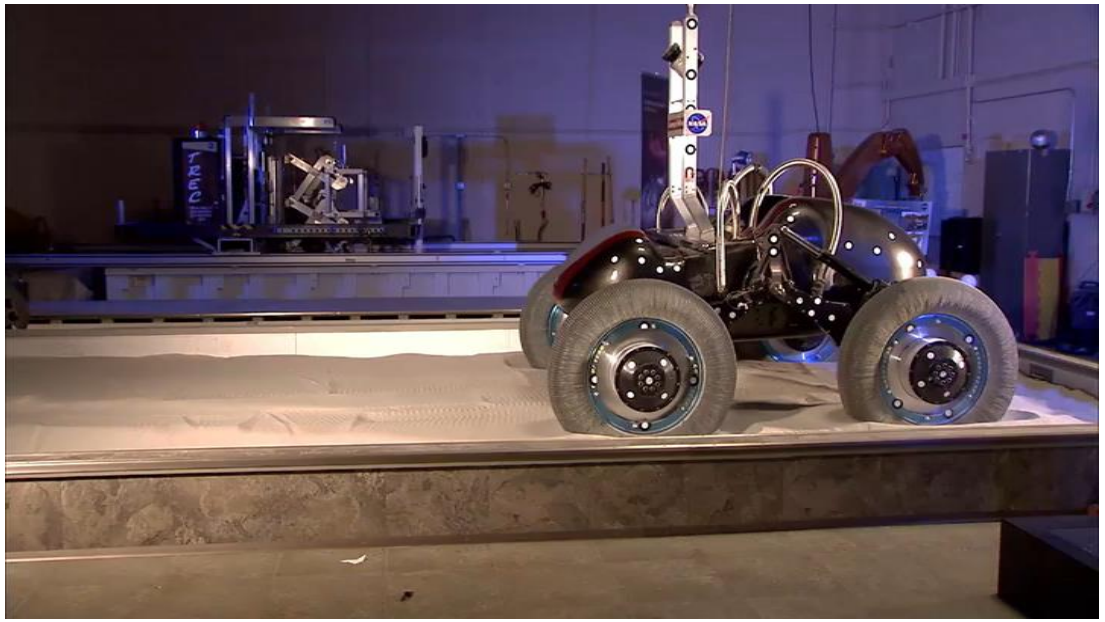
$$\arg\min_{n_1,n_2}\{(l_{clr}-l^*_{clr}(x))^2 \mid x = g(n_1,n_2)\}$$

$$n_1^i \le n_1 \le n_1^f \qquad n_2^i \le n_2 \le n_2^f$$

2D stochastic parameter optimization

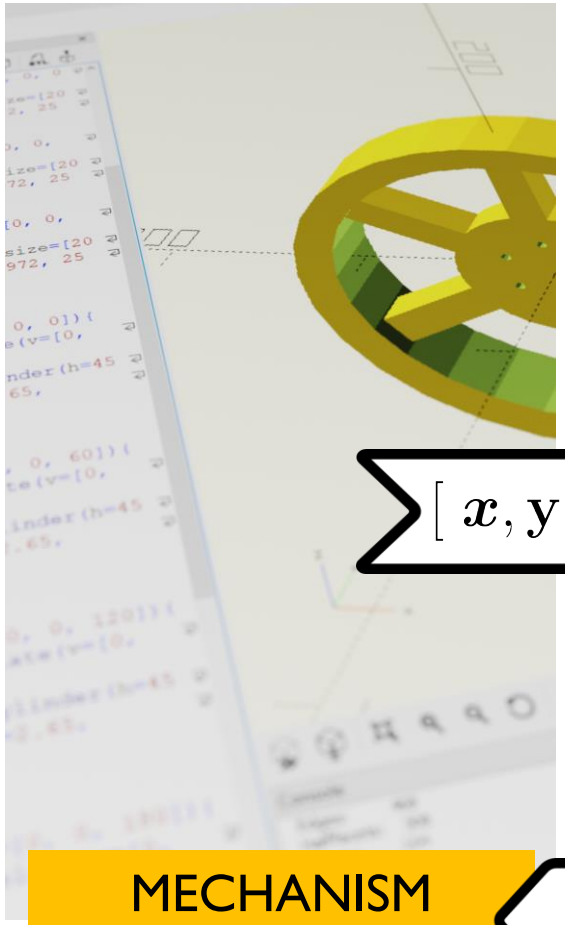
MOBILITY RESEARCH IN NASA GRC SLOPE LAB

Rigid wheel testing of NASA's VIPER and JPL's CADRE

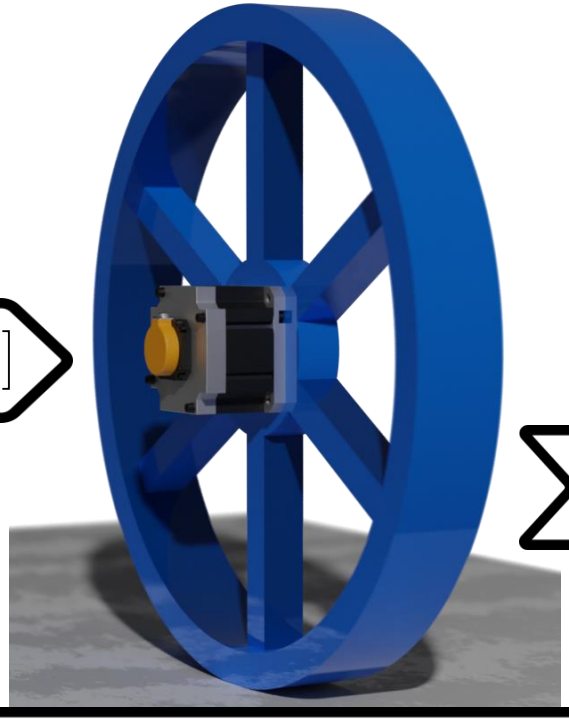


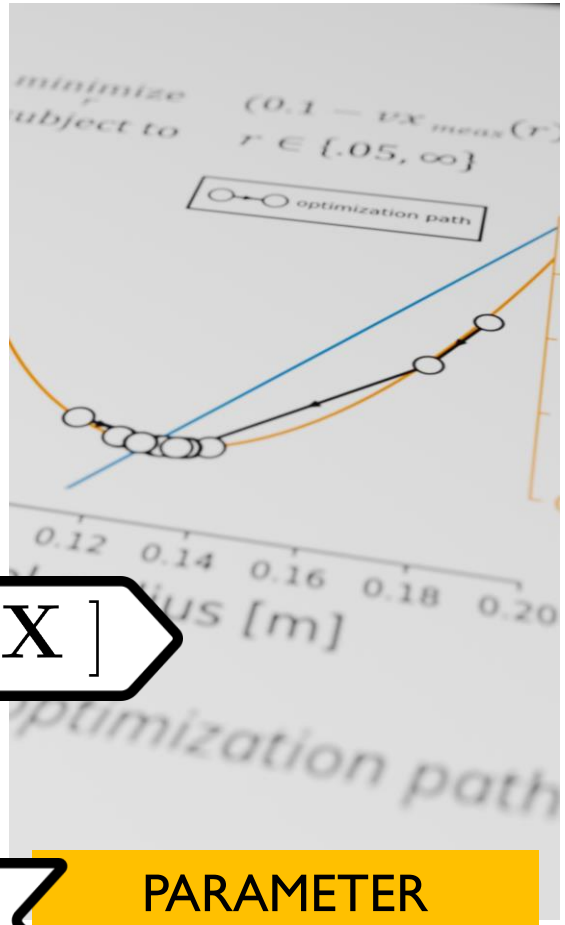
Non-pneumatic spring tire testing on the Scarab rover

MECHANISM OPTIMIZATION TOOLCHAIN



SYSTEM SIMULATION





$[\ x, y, z\ ]$

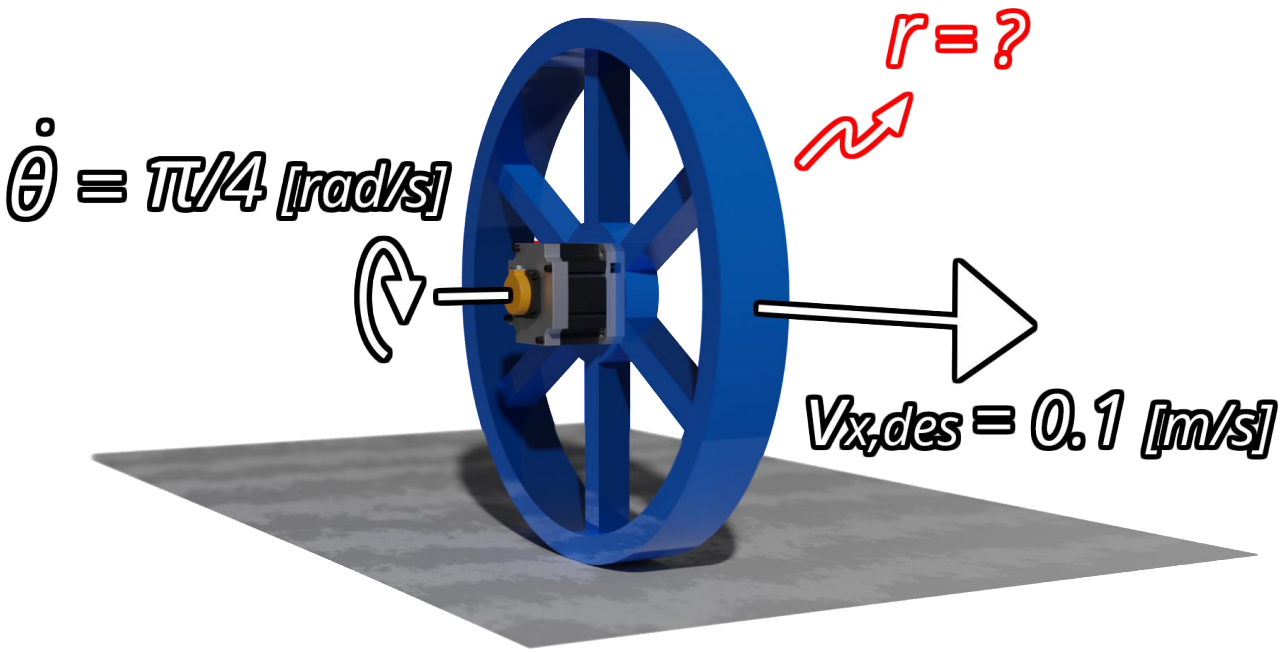
$[\ X\ ]$

MECHANISM GENERATION

$[\ d_1, d_2, ...d_n\ ]$

PARAMETER OPTIMIZATION

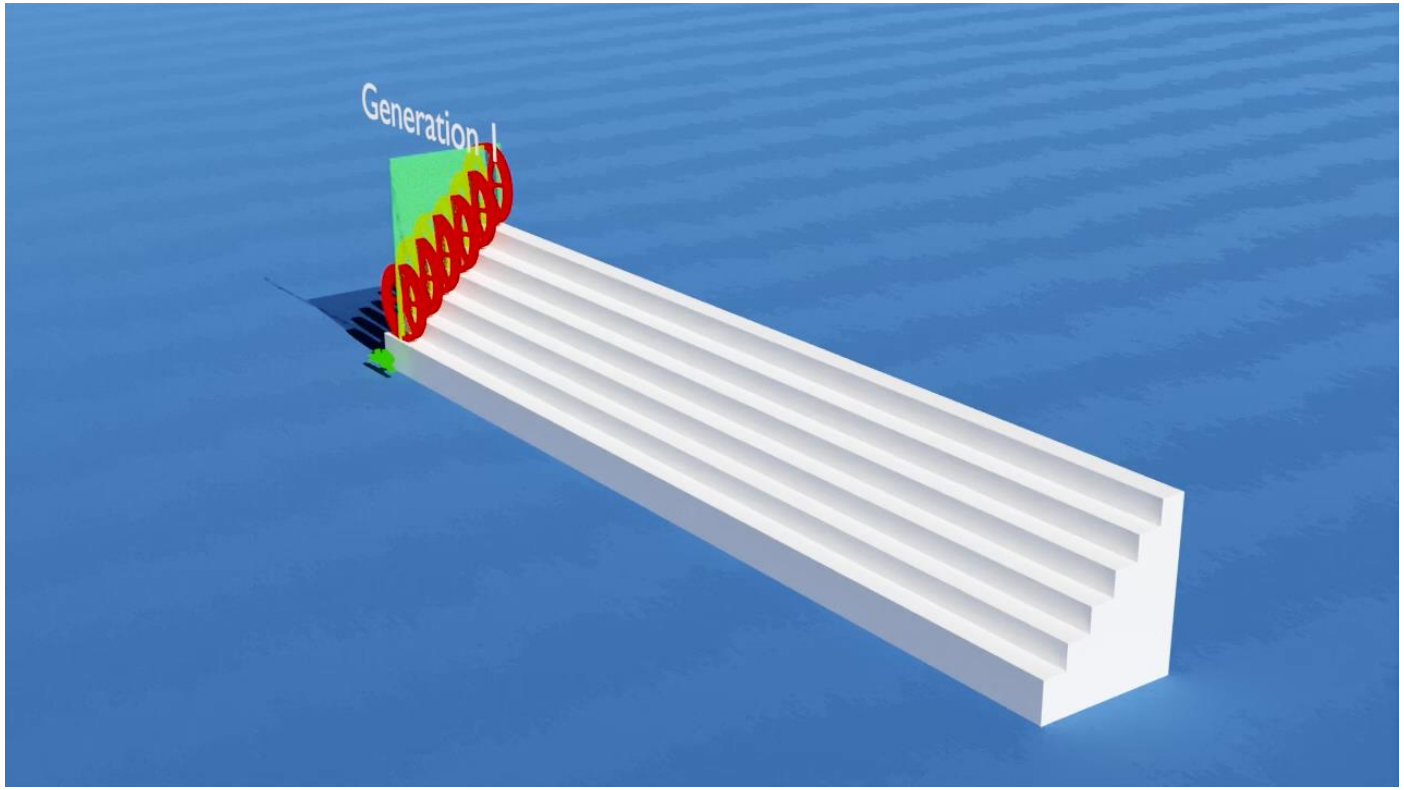
EXAMPLE: WHEEL RADIUS OPTIMIZATION



Wheel mechanism

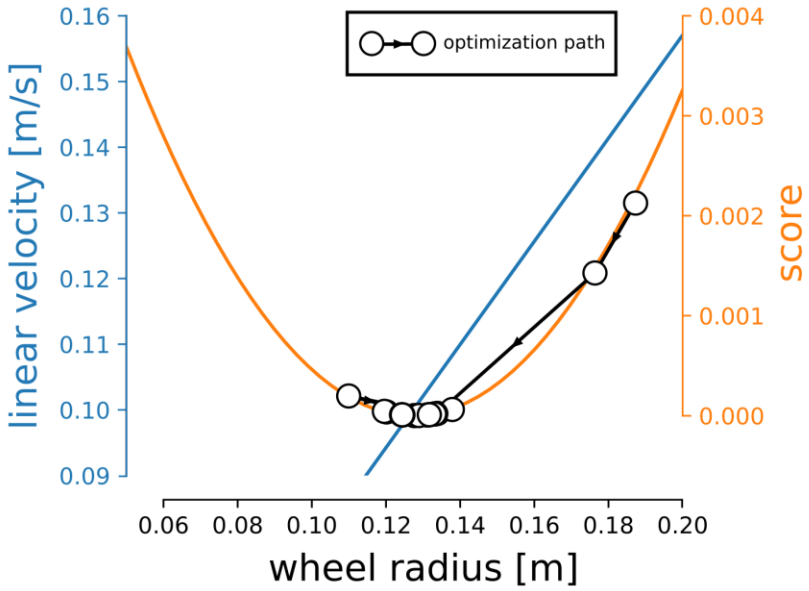
- **Analytically:**
  - $v = r\dot{\theta}$
  - $r = 127.3\ [mm]$

EXAMPLE: WHEEL RADIUS OPTIMIZATION (CONT'D)



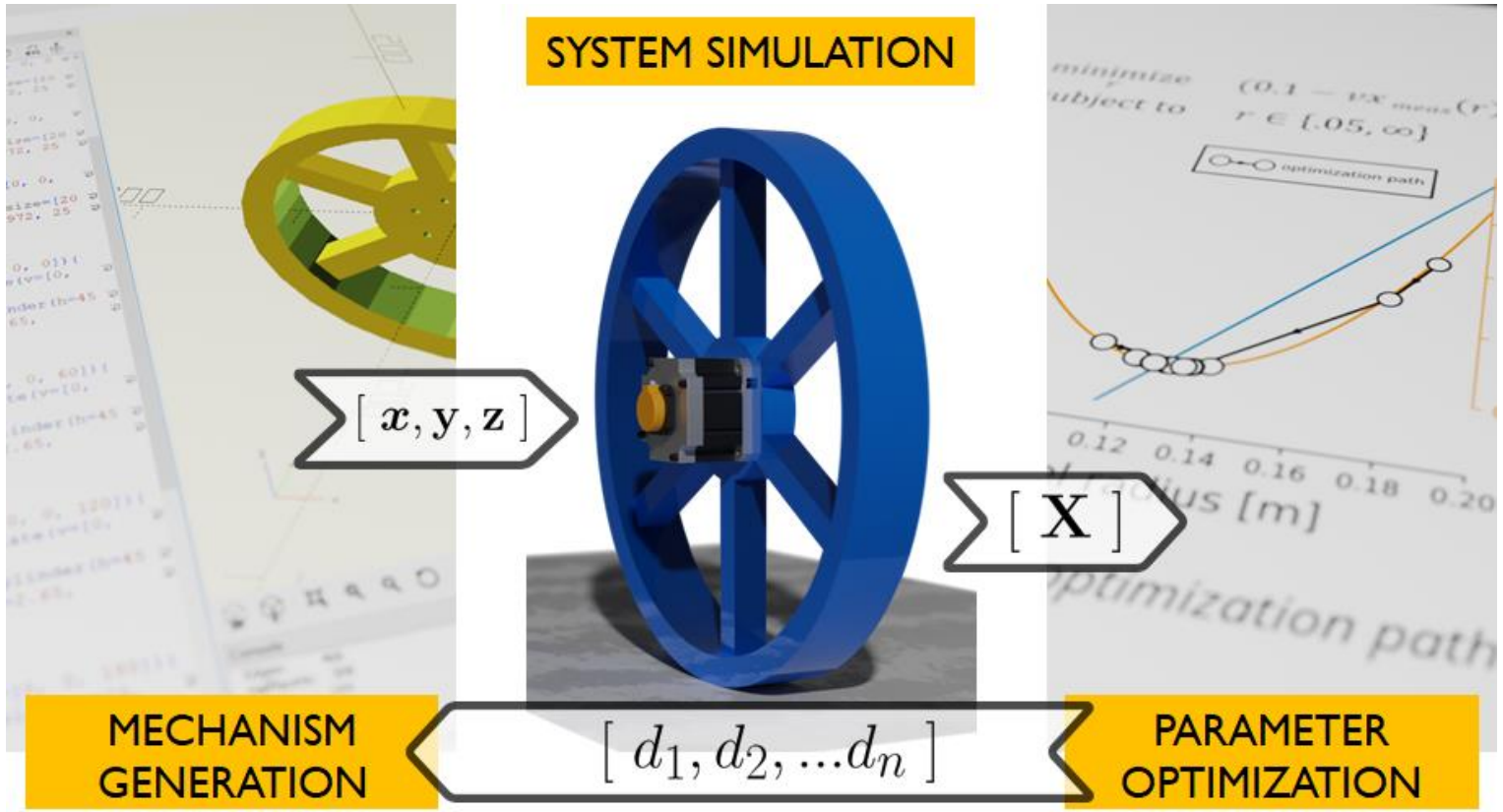
Wheel radius optimization in simulation environment via CMA-ES [3]

$$\underset{r}{\text{minimize}} \quad g(r) = (0.1 - vx_{meas}(r))^2$$
$$\text{subject to} \quad r \in \{.05, \infty\}$$

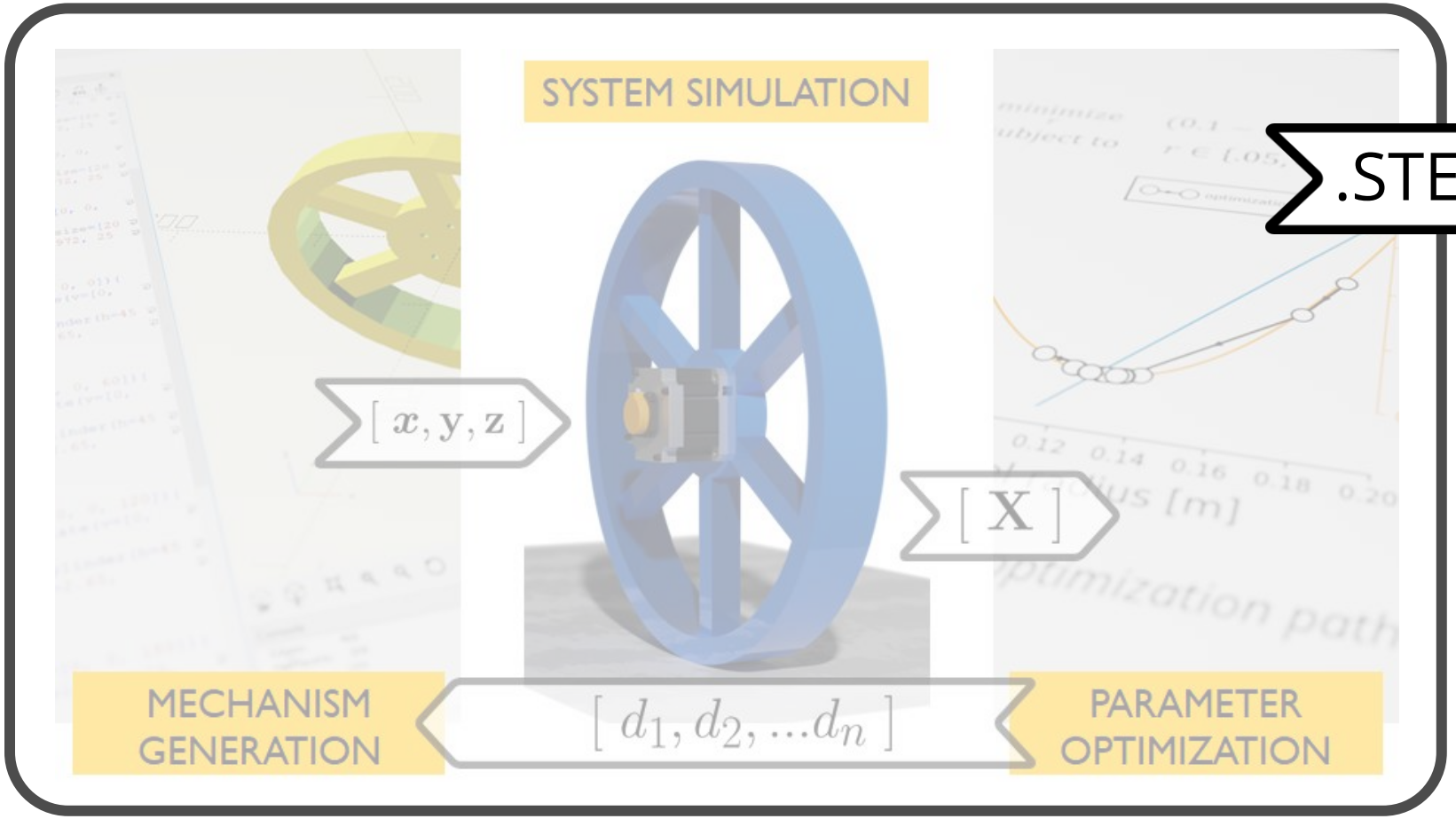


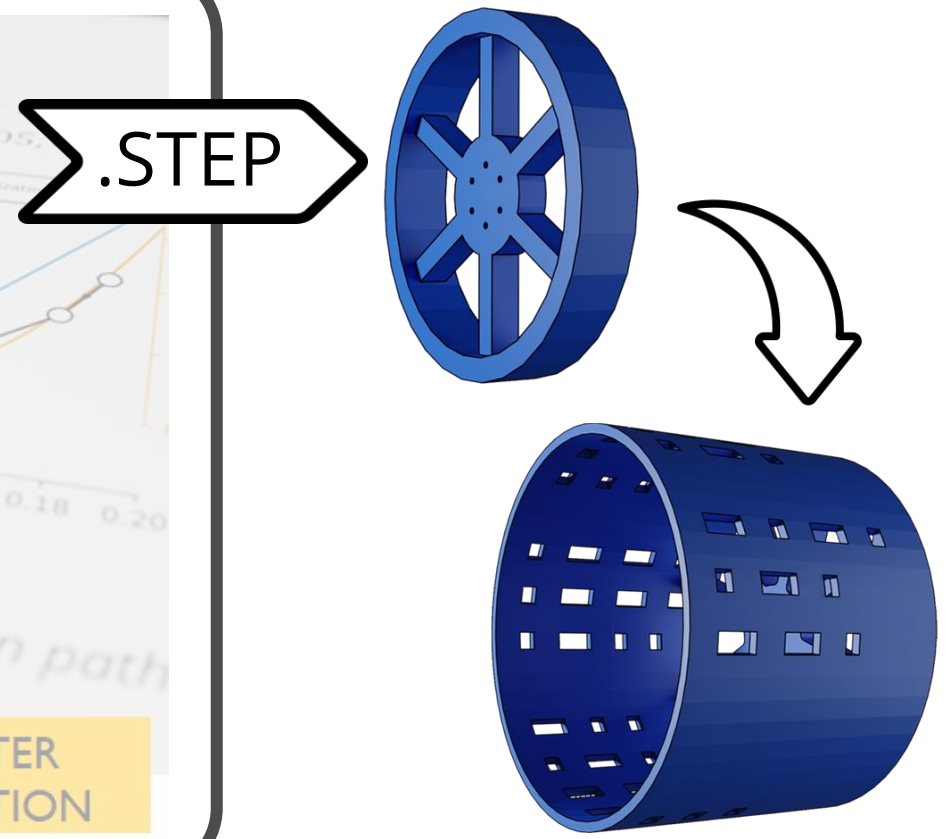
Cost space and optimization path

MECHANISM DESIGN TOOLCHAIN

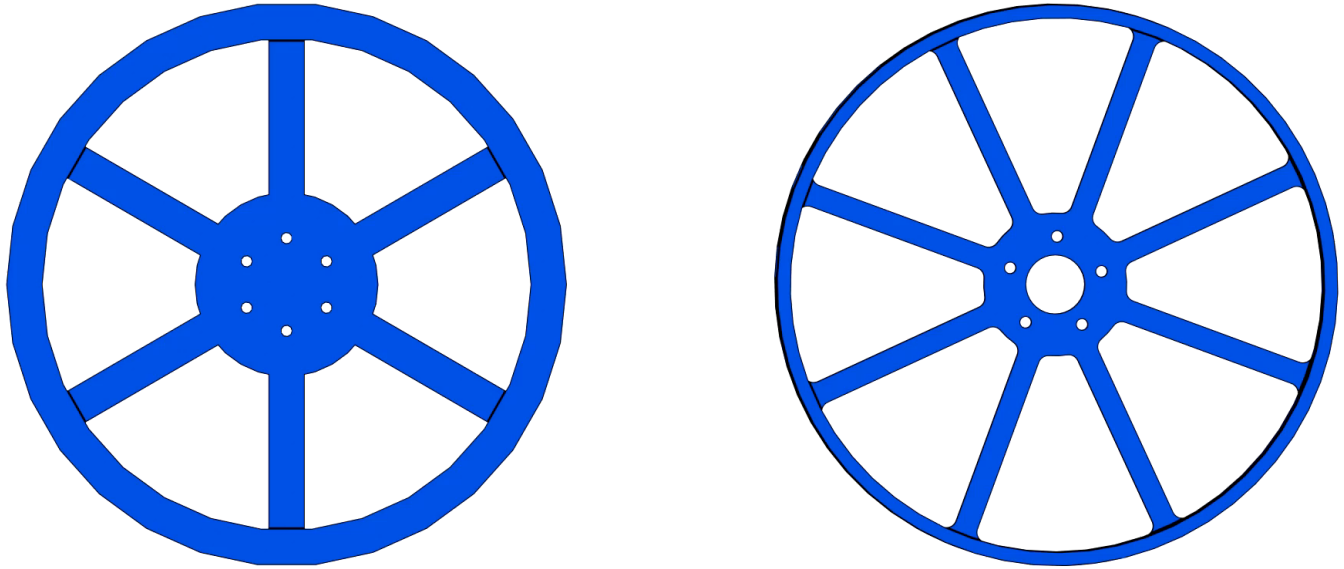


MECHANISM DESIGN TOOLCHAIN





OPTIMIZED MECHANISMS ARE PARAMETRIC AND REMAIN FULLY EDITABLE



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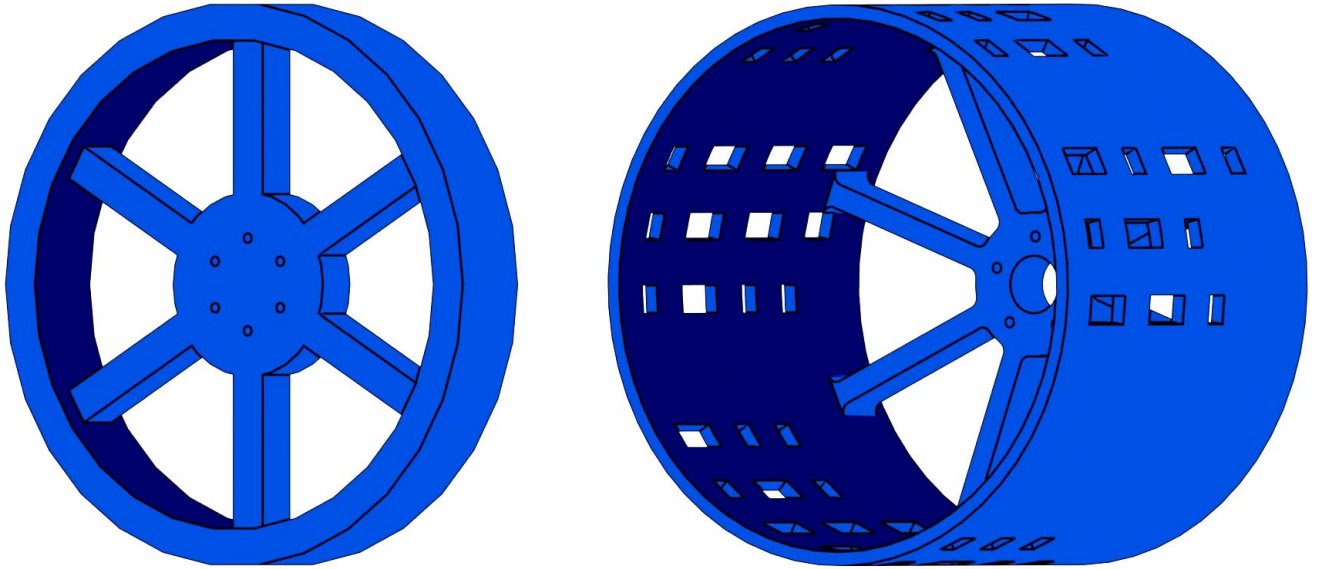

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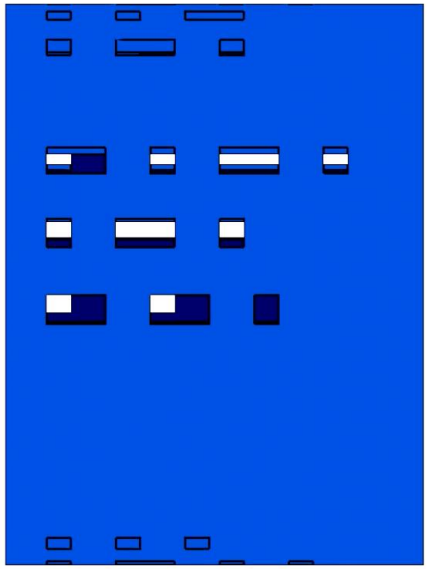
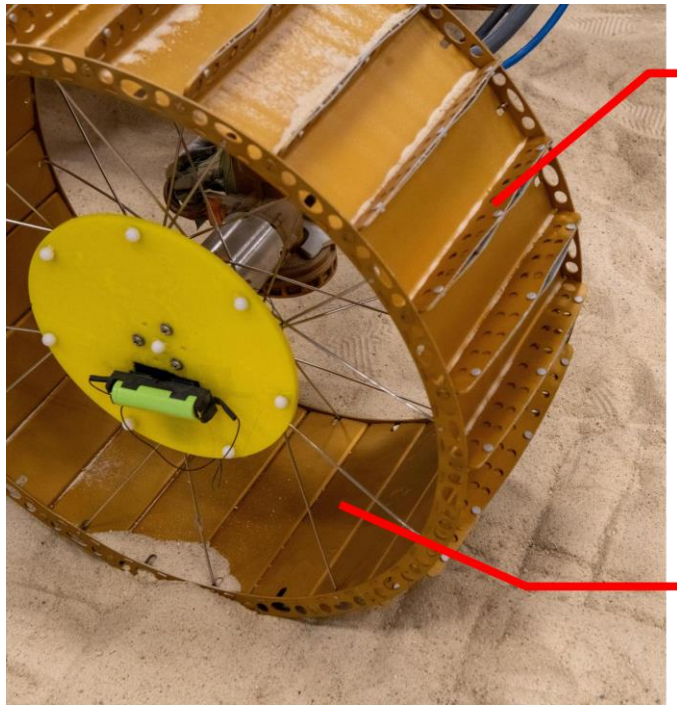
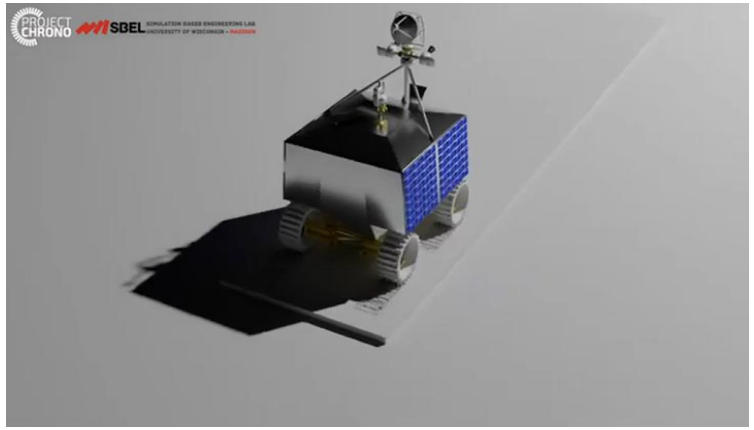


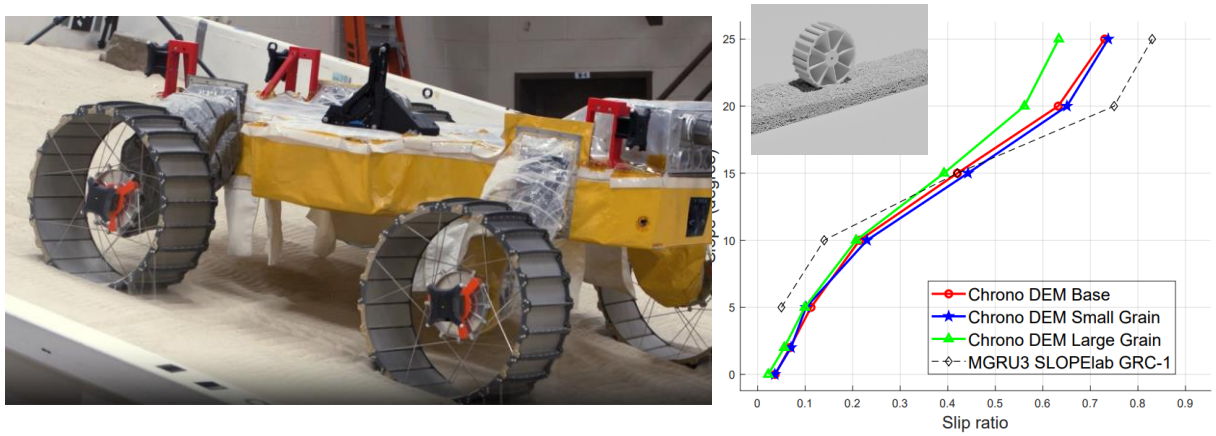
MULTI-DIMENSIONAL RIGID WHEEL OPTIMIZATION



Mobility-related features of a rigid wheel

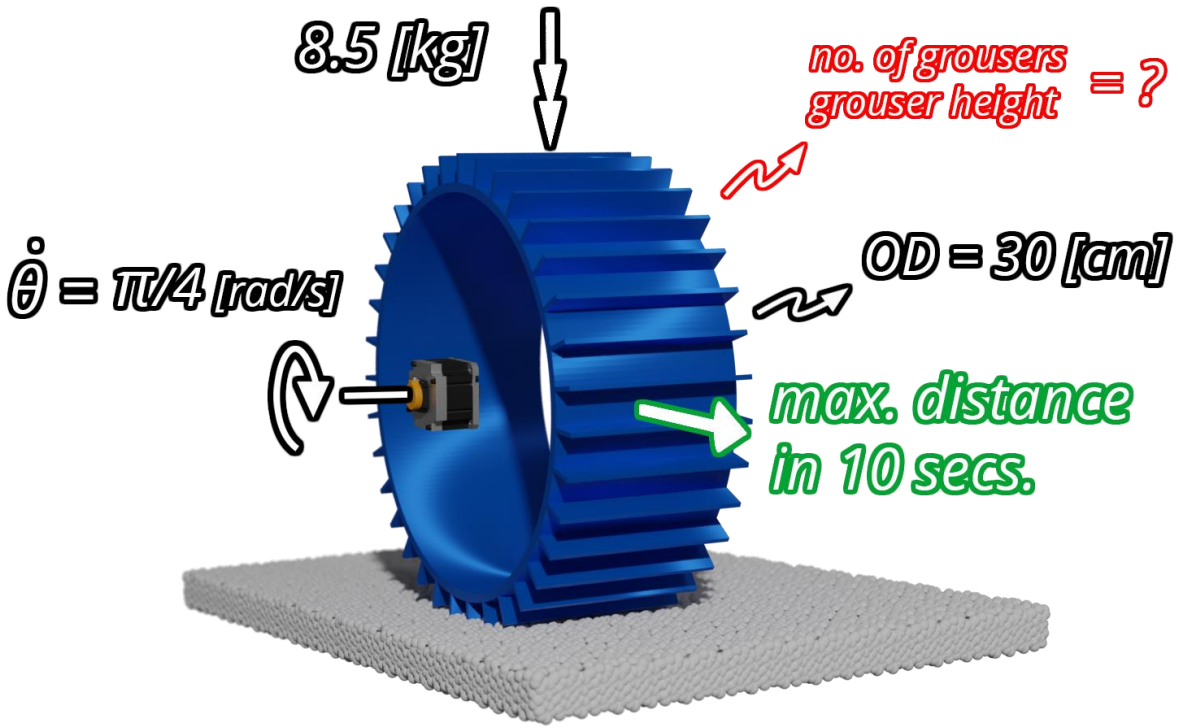


VIPER simulation in Chrono [4]



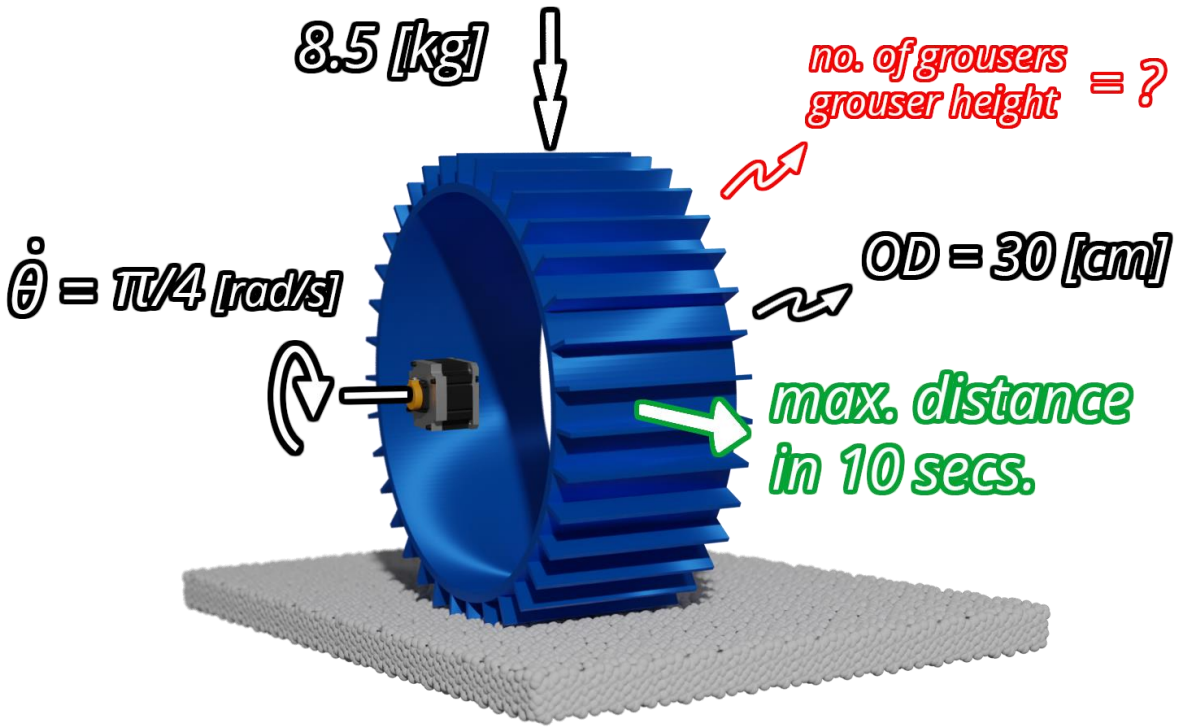
Chrono validation via VIPER SLOPE tests [5]

MULTI-DIMENSIONAL RIGID WHEEL OPTIMIZATION



2D wheel optimization problem in granular media

MULTI-DIMENSIONAL RIGID WHEEL OPTIMIZATION



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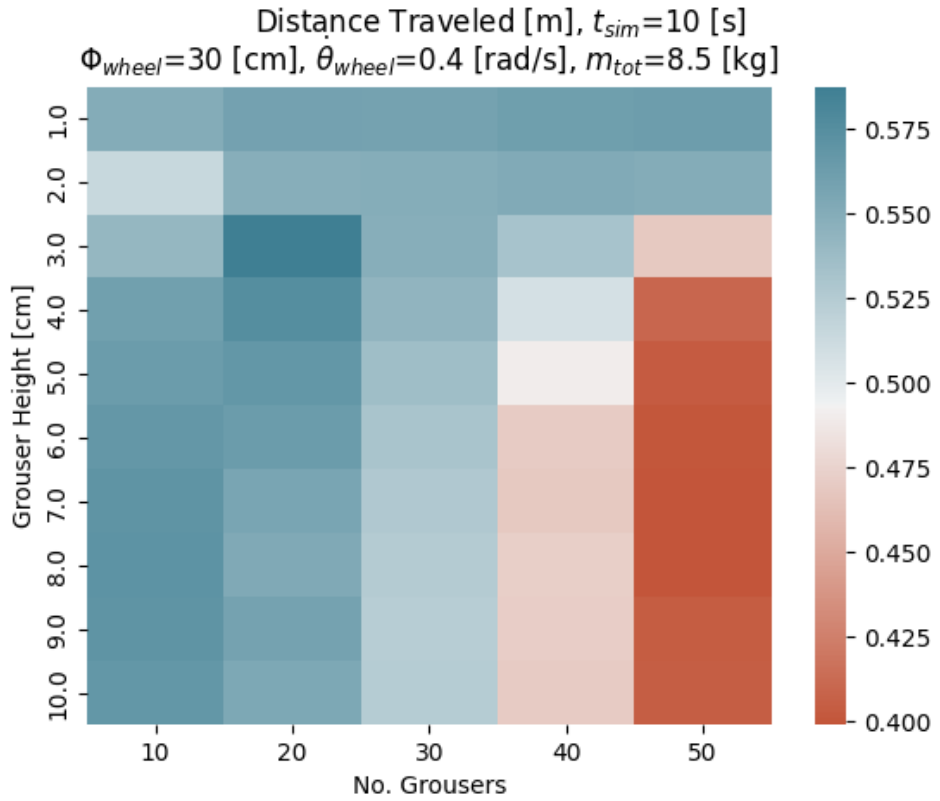
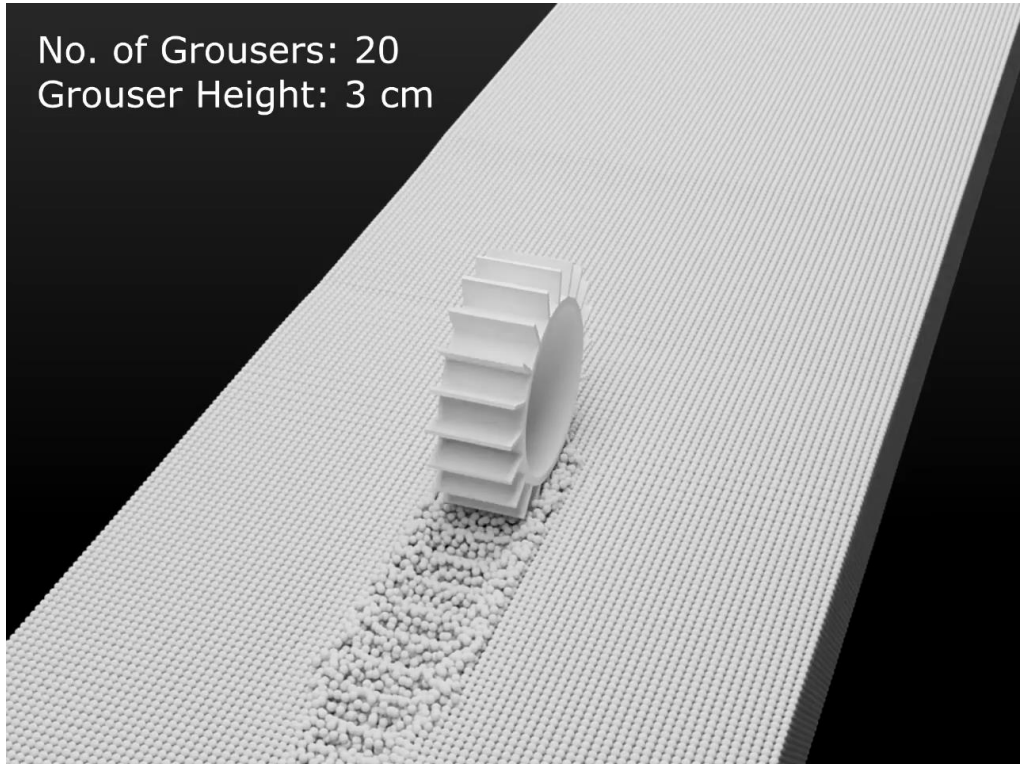
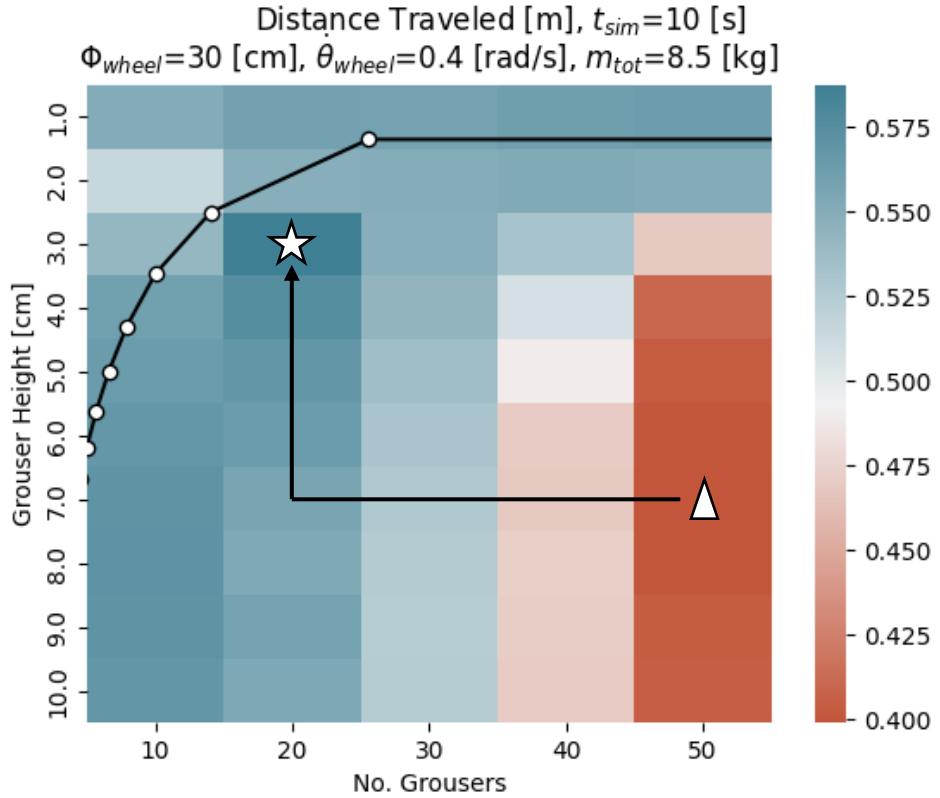


Design space parameter sweep (simulated in Chrono [6])

MULTI-DIMENSIONAL RIGID WHEEL OPTIMIZATION

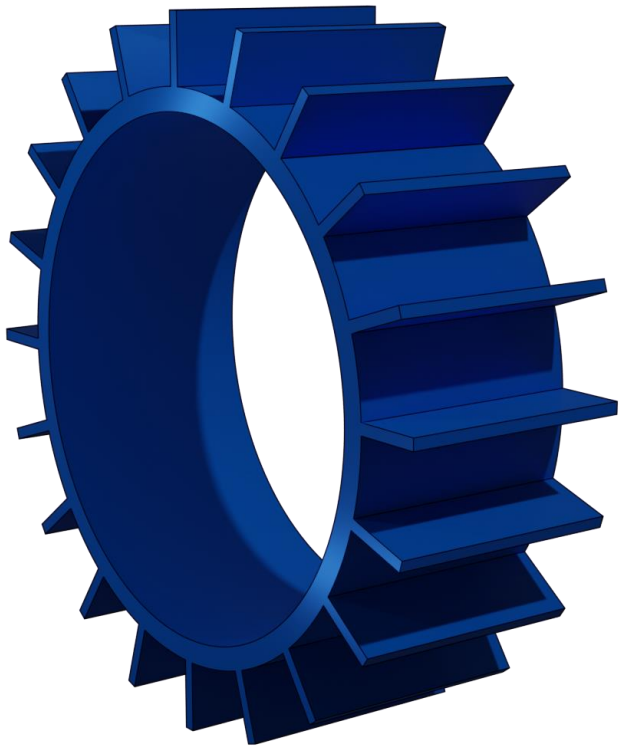


Wheel simulations

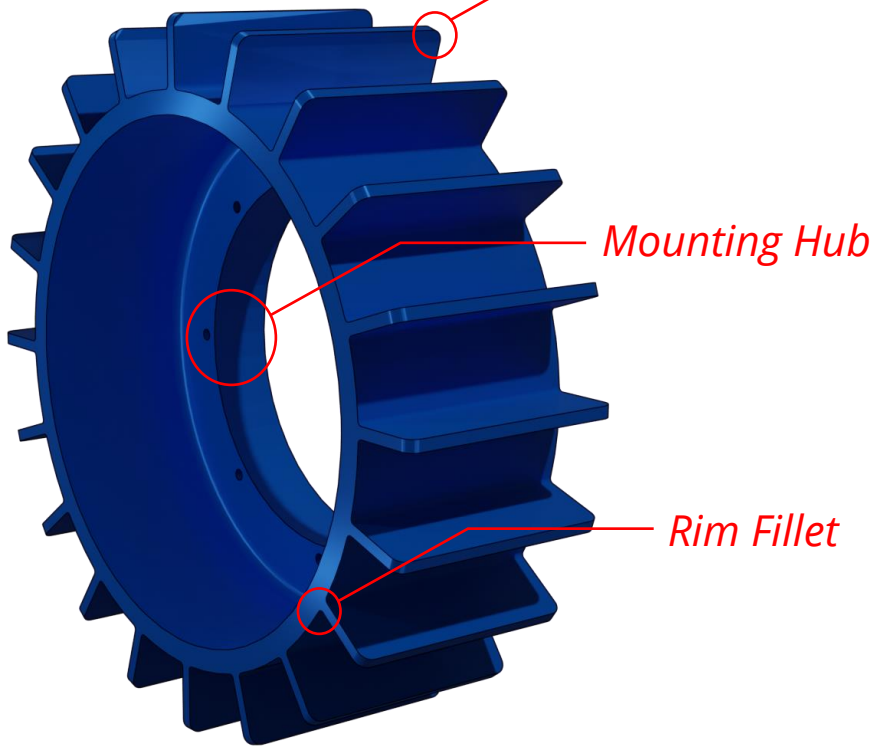


Parameter optimization using discrete hill climbing
(△→☆: Optimization path. ○: Optimum design at 20% slip suggested by [7])

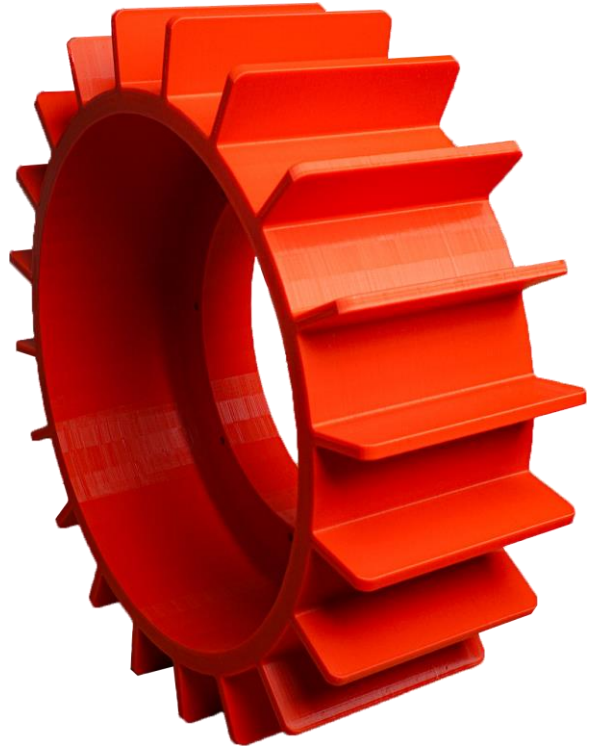
WHEEL MANUFACTURE



Optimized wheel

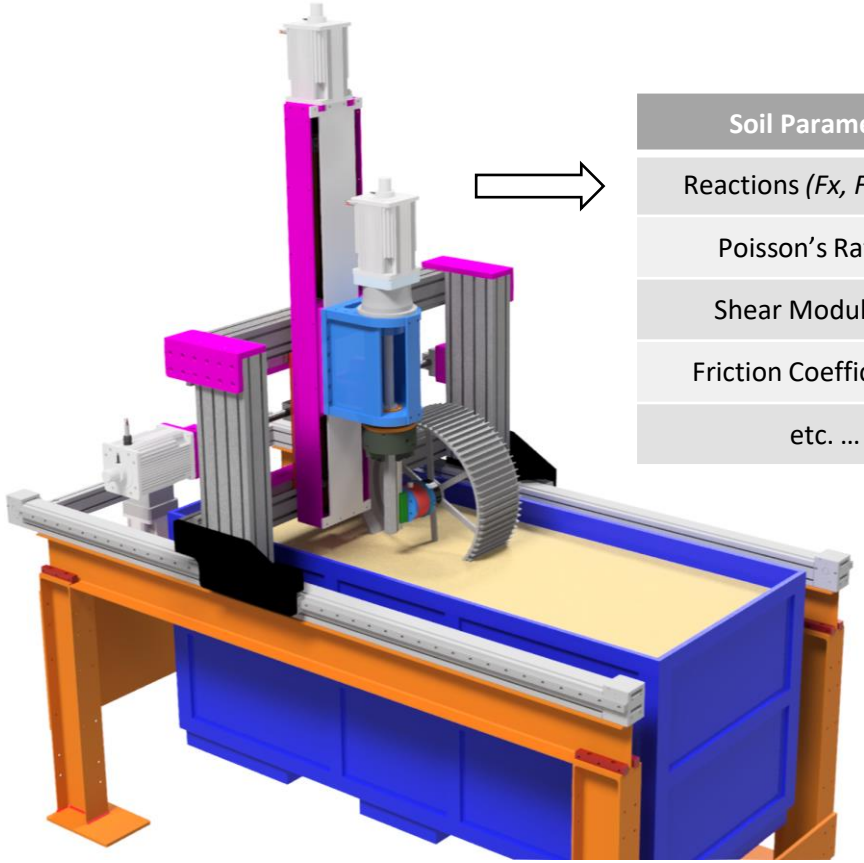


User-modified wheel CAD model



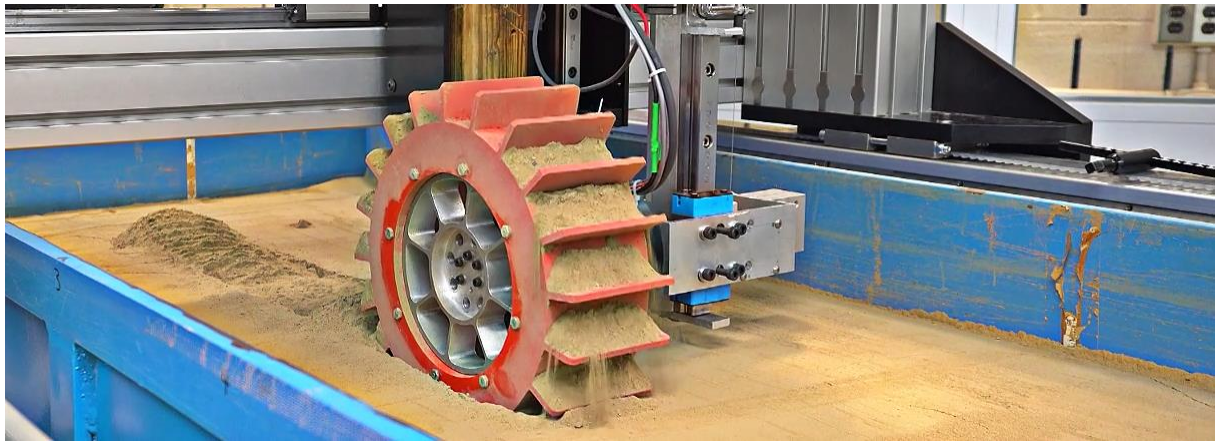
Additively manufactured wheel

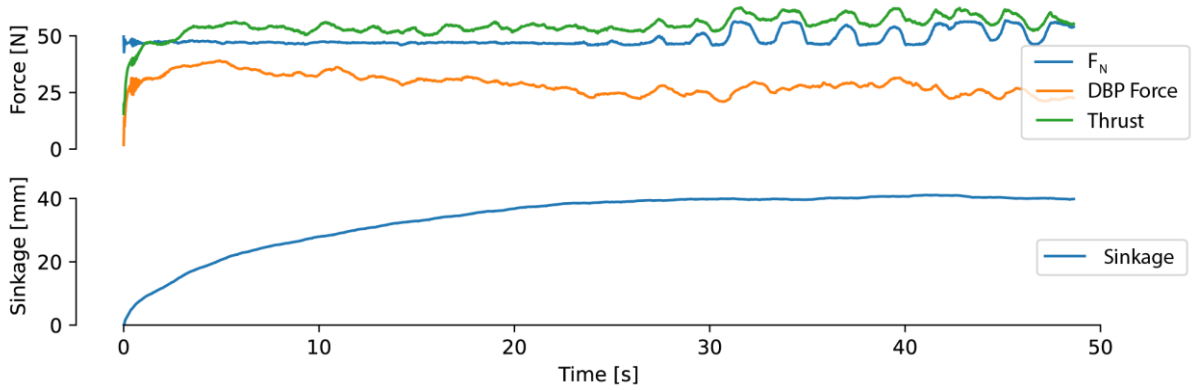
PRELIMINARY WHEEL TESTING



Soil Parameters
Reactions *(Fx, Fy, … Mz)*
Poisson's Ratio *(v)*
Shear Modulus *(G)*
Friction Coefficient *(μ)*
etc. …

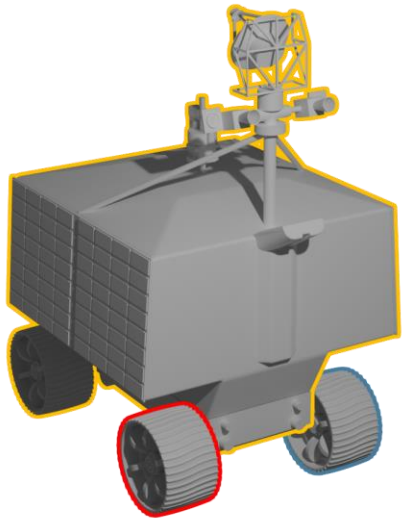
GRC soil characterization rig

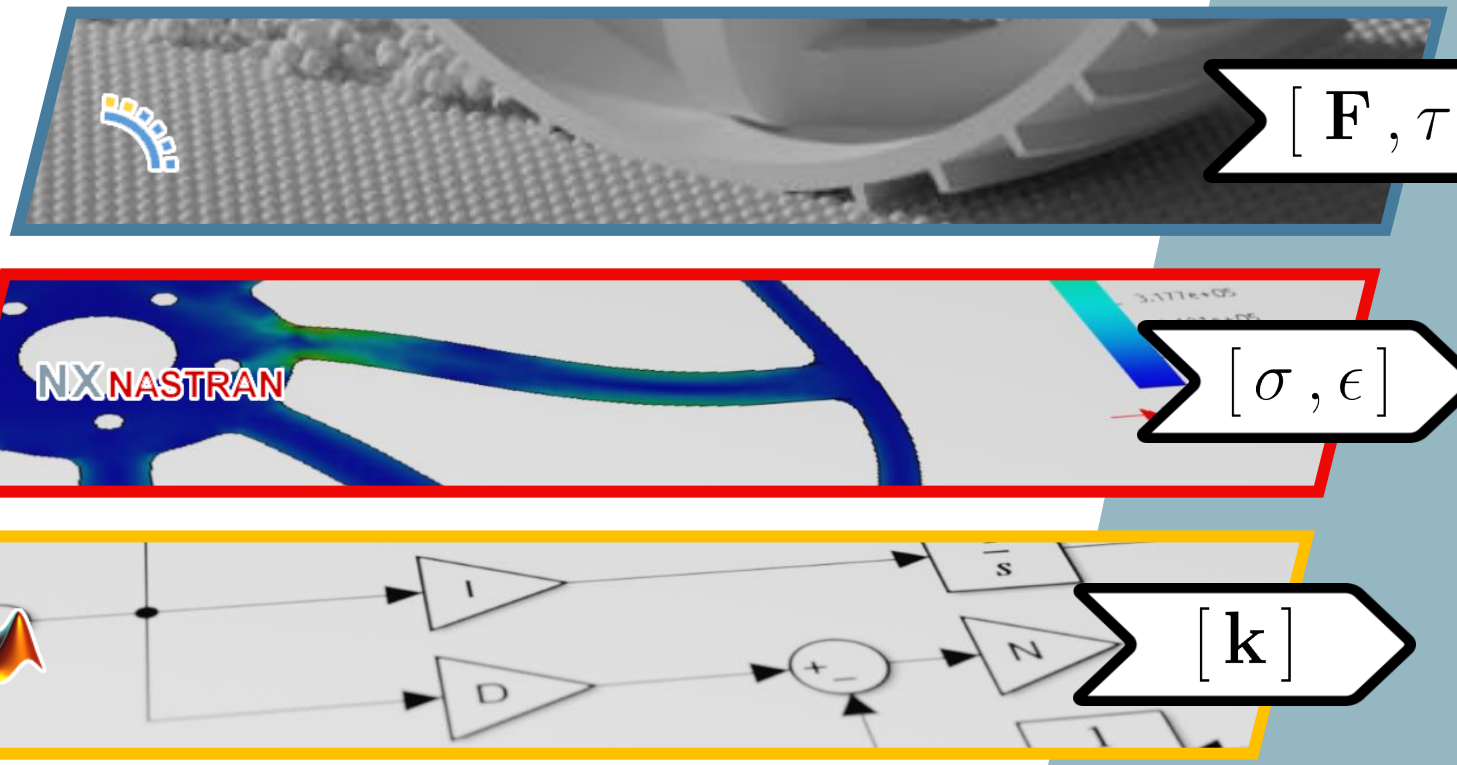




Drawbar pull (DBP) testing with optimized wheel in GRC-3b [8]
(Slip controlled to be 54% (v_{ref}=1.67 [cm/s], v=0.77 [cm/s]))

MULTI-OBJECTIVE FORMULATION ENABLES MODULARITY AND CO-OPTIMIZATION



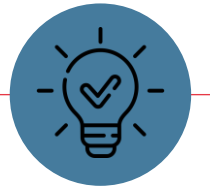


$[\mathbf{F}, \tau]$

$[\sigma, \epsilon]$

$g(\mathbf{x})$

$[\mathbf{k}]$



SUMMARY

- We have developed a modular mechanism optimization tool
- Outputs parametric CAD that can be further post-processed
- Can leverage high-fidelity simulation tools for virtual design
- Simulation calibration and validation is in progress
- Toolchain development is ongoing (comparison to [7])

THANK YOU! QUESTIONS?

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Sources:
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