

Wing Design Via SAIL

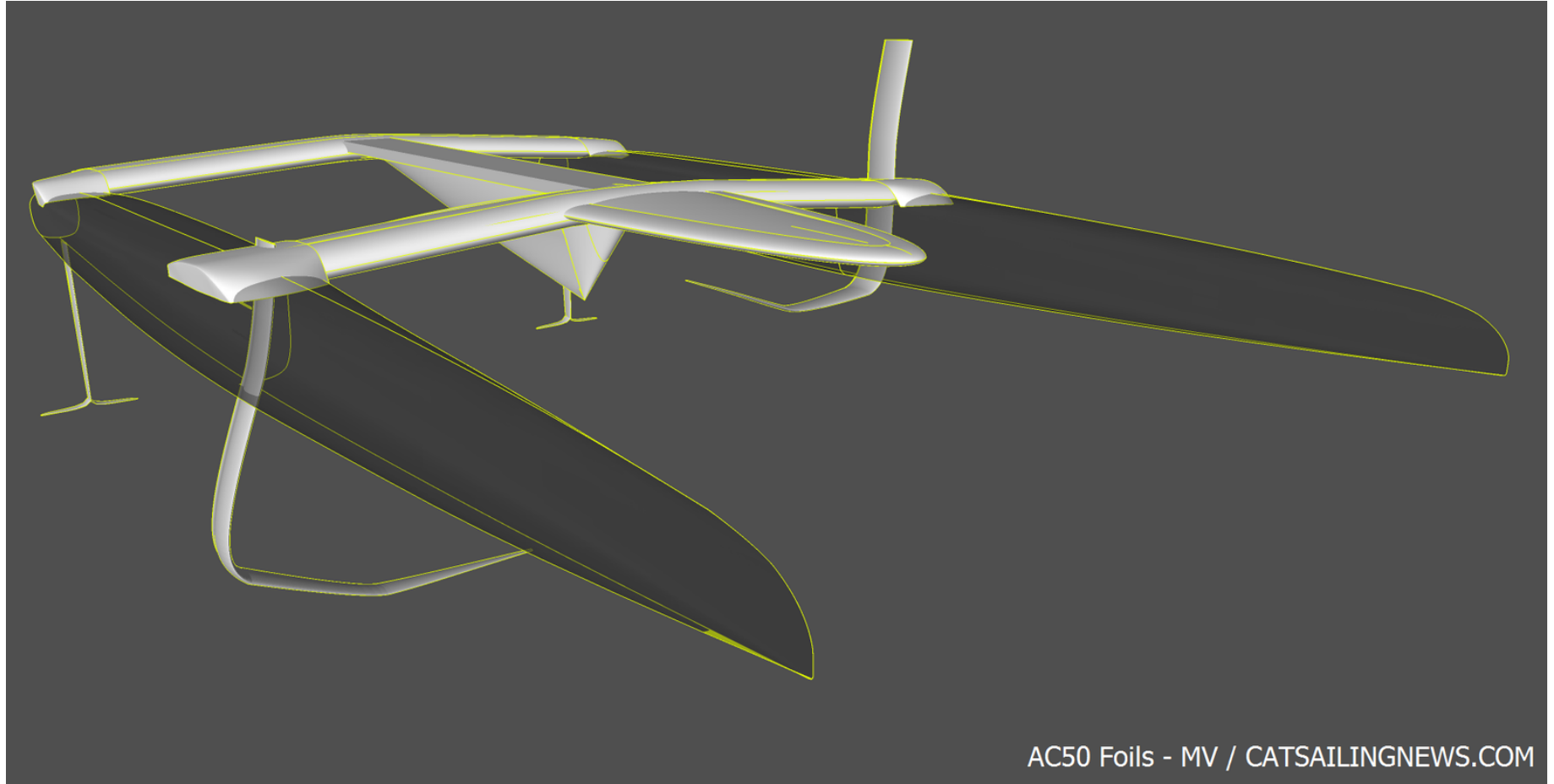
Leonid Scott

Spring 2019 Computer Science Senior
Seminar

University of Minnesota Morris



<https://www.southernspars.com/wp-content/uploads/2017/06/RG170611AmCupL2R5compressed.png>



AC50 Foils - MV / CATSAILINGNEWS.COM

Foil design is hard

Foil design is hard

Navier Stokes

$$\begin{aligned} r : \quad & \rho \left(\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{u_\phi}{r \sin(\theta)} \frac{\partial u_r}{\partial \phi} + \frac{u_\theta}{r} \frac{\partial u_r}{\partial \theta} - \frac{u_\phi^2 + u_\theta^2}{r} \right) = -\frac{\partial p}{\partial r} + \rho g_r + \\ & \mu \left[\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial u_r}{\partial r} \right) + \frac{1}{r^2 \sin(\theta)^2} \frac{\partial^2 u_r}{\partial \phi^2} + \frac{1}{r^2 \sin(\theta)} \frac{\partial}{\partial \theta} \left(\sin(\theta) \frac{\partial u_r}{\partial \theta} \right) - 2 \frac{u_r + \frac{\partial u_\theta}{\partial \theta} + u_\theta \cot(\theta)}{r^2} - \frac{2}{r^2 \sin(\theta)} \frac{\partial u_\phi}{\partial \phi} \right] \\ \phi : \quad & \rho \left(\frac{\partial u_\phi}{\partial t} + u_r \frac{\partial u_\phi}{\partial r} + \frac{u_\phi}{r \sin(\theta)} \frac{\partial u_\phi}{\partial \phi} + \frac{u_\theta}{r} \frac{\partial u_\phi}{\partial \theta} + \frac{u_r u_\phi + u_\phi u_\theta \cot(\theta)}{r} \right) = -\frac{1}{r \sin(\theta)} \frac{\partial p}{\partial \phi} + \rho g_\phi + \\ & \mu \left[\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial u_\phi}{\partial r} \right) + \frac{1}{r^2 \sin(\theta)^2} \frac{\partial^2 u_\phi}{\partial \phi^2} + \frac{1}{r^2 \sin(\theta)} \frac{\partial}{\partial \theta} \left(\sin(\theta) \frac{\partial u_\phi}{\partial \theta} \right) + \frac{2 \sin(\theta) \frac{\partial u_r}{\partial \phi} + 2 \cos(\theta) \frac{\partial u_\theta}{\partial \phi} - u_\phi}{r^2 \sin(\theta)^2} \right] \\ \theta : \quad & \rho \left(\frac{\partial u_\theta}{\partial t} + u_r \frac{\partial u_\theta}{\partial r} + \frac{u_\phi}{r \sin(\theta)} \frac{\partial u_\theta}{\partial \phi} + \frac{u_\theta}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{u_r u_\theta - u_\phi^2 \cot(\theta)}{r} \right) = -\frac{1}{r} \frac{\partial p}{\partial \theta} + \rho g_\theta + \\ & \mu \left[\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial u_\theta}{\partial r} \right) + \frac{1}{r^2 \sin(\theta)^2} \frac{\partial^2 u_\theta}{\partial \phi^2} + \frac{1}{r^2 \sin(\theta)} \frac{\partial}{\partial \theta} \left(\sin(\theta) \frac{\partial u_\theta}{\partial \theta} \right) + \frac{2}{r^2} \frac{\partial u_r}{\partial \theta} - \frac{u_\theta + 2 \cos(\theta) \frac{\partial u_\phi}{\partial \phi}}{r^2 \sin(\theta)^2} \right]. \end{aligned}$$

https://en.wikipedia.org/wiki/Navier%E2%80%93Stokes_equations

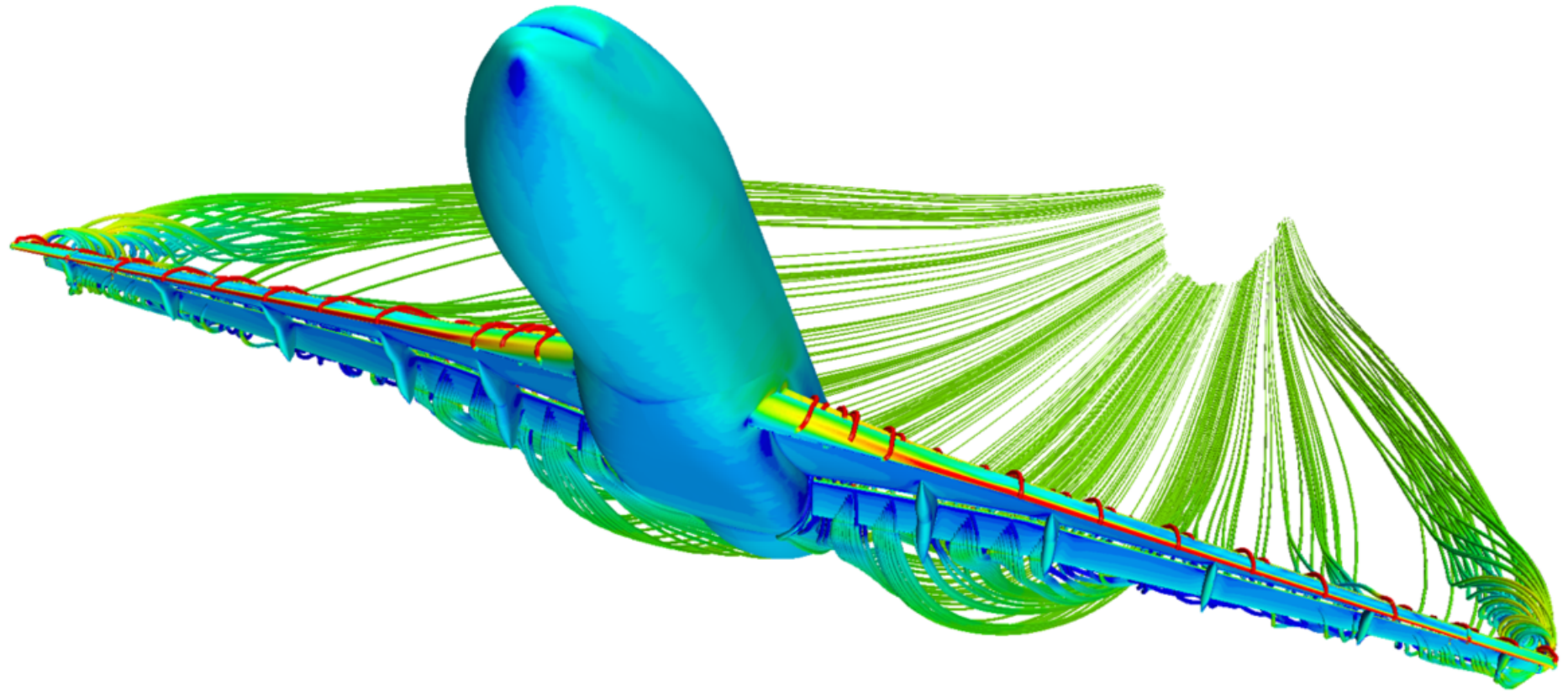
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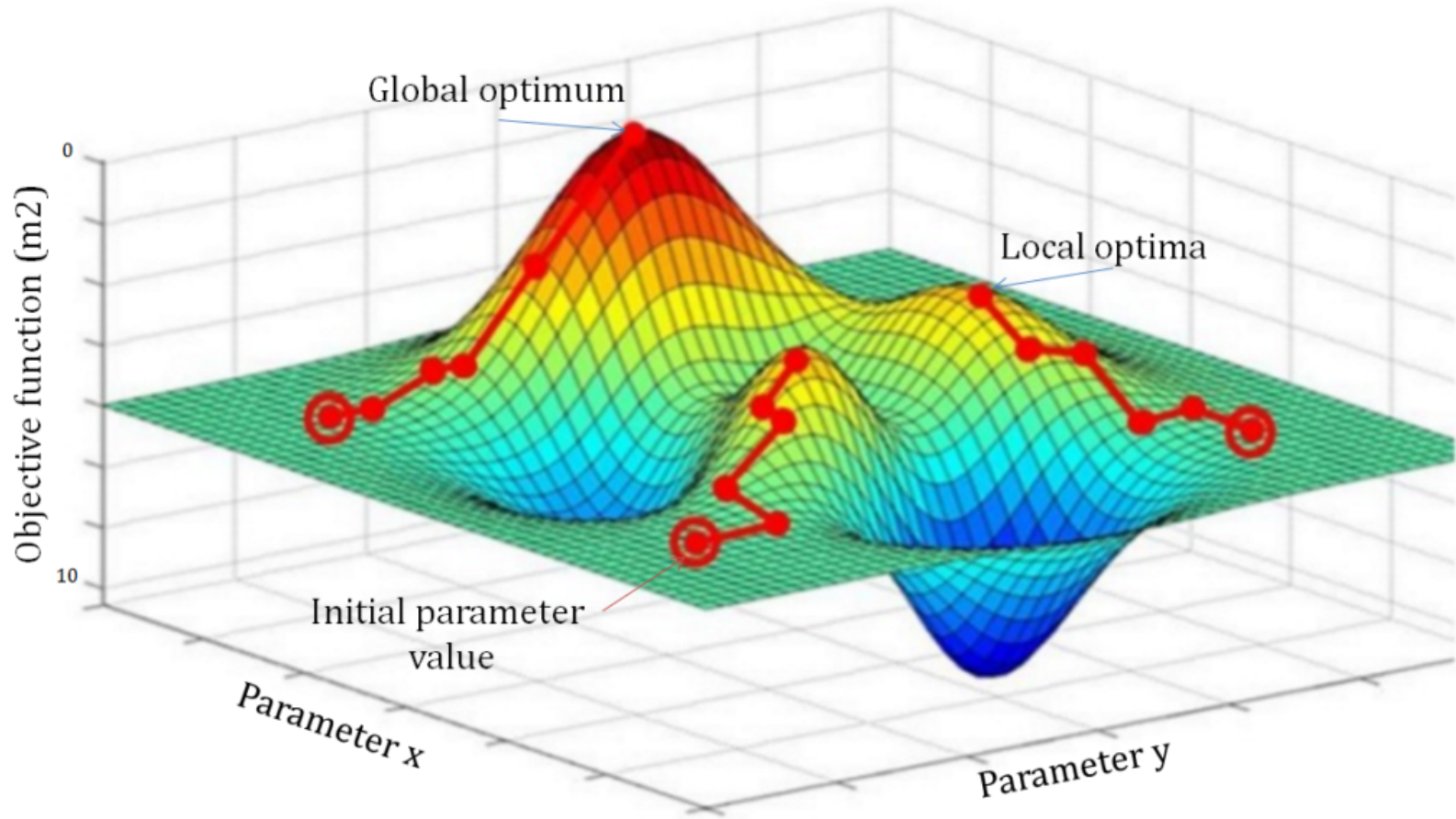
https://en.wikipedia.org/wiki/Navier%E2%80%93Stokes_equations

Computational Fluid Dynamics (CFD)



<http://www.oerc.ox.ac.uk/news/ashton-focus>

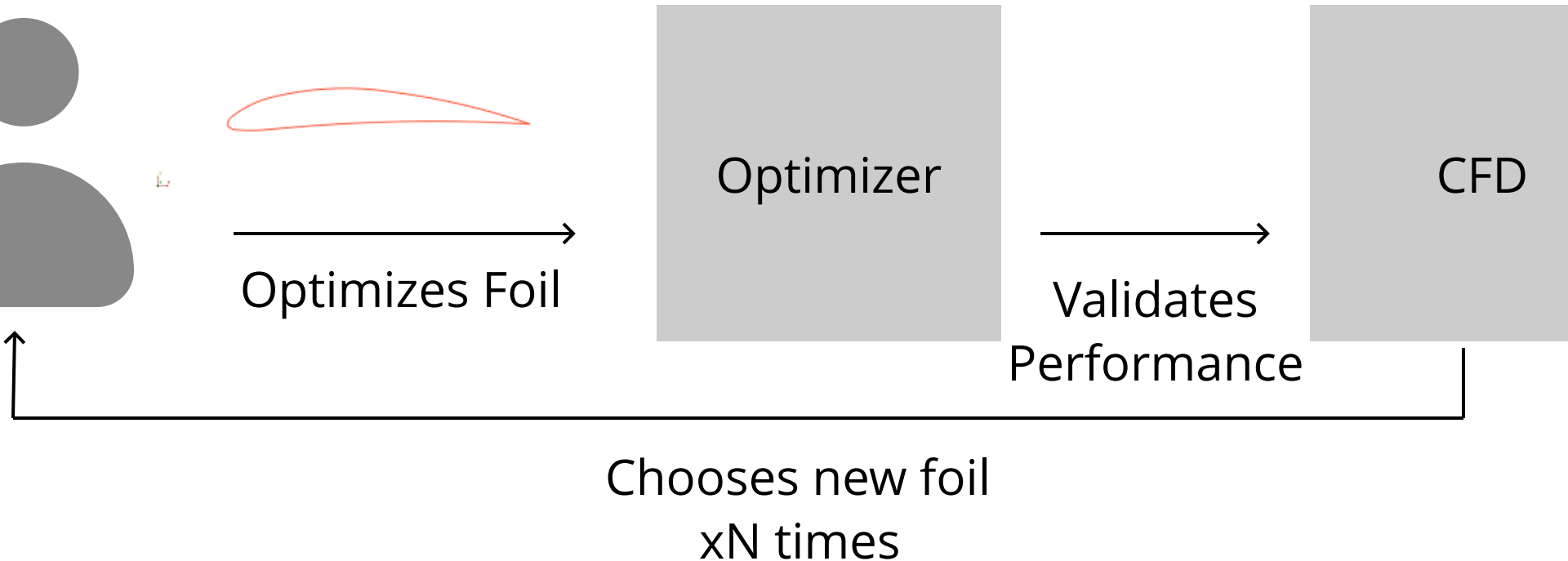
Optimizers



Optimizers

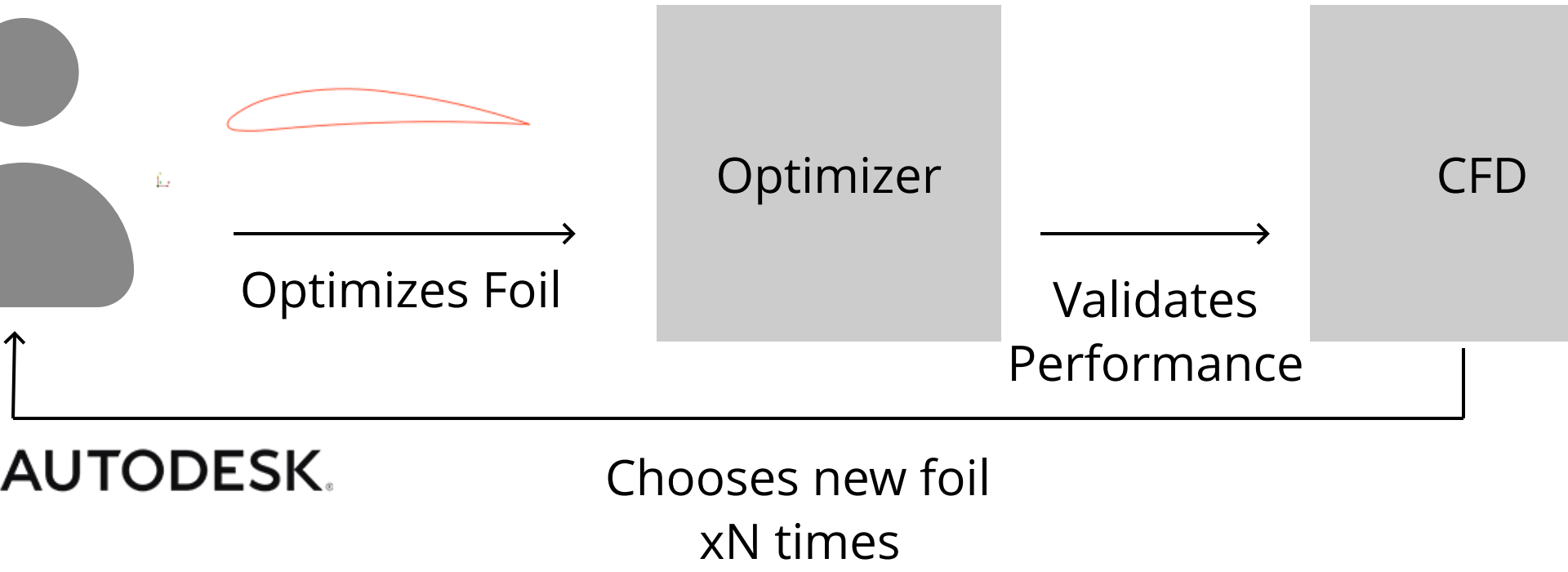
AUTODESK®

Extended Design Cycle



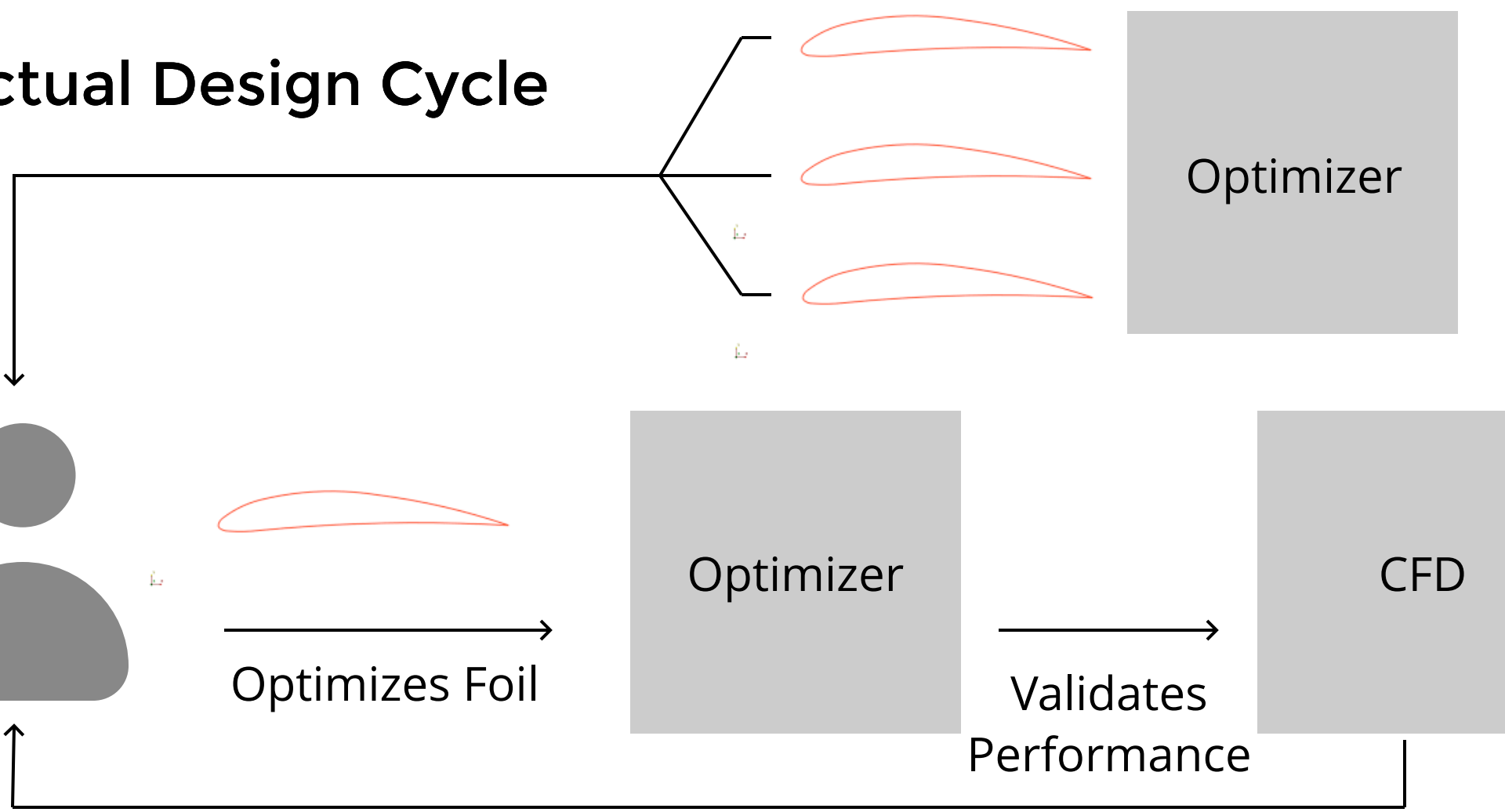
Optimizers

Actual Design Cycle



Optimizers

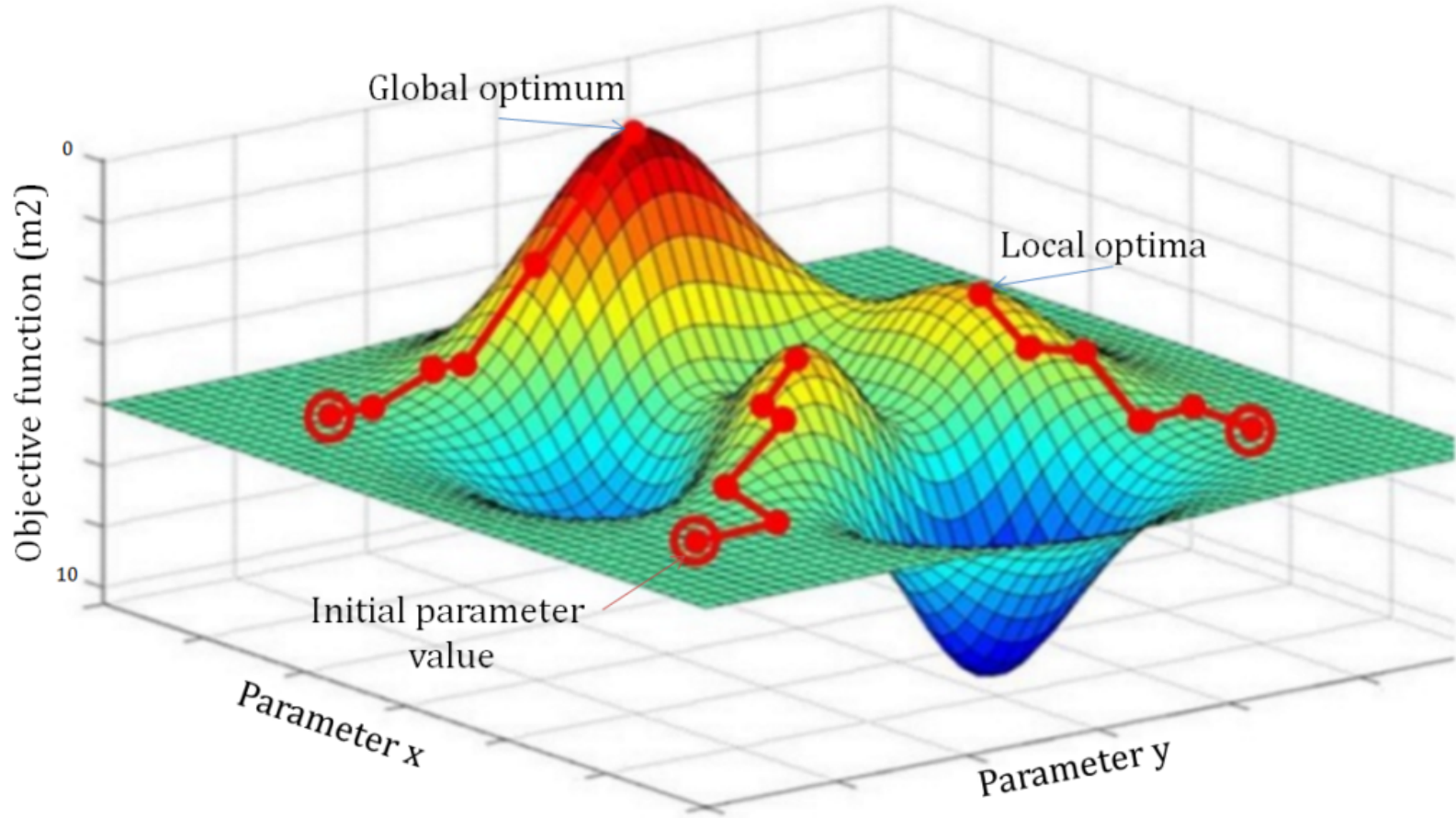
Actual Design Cycle



AUTODESK®

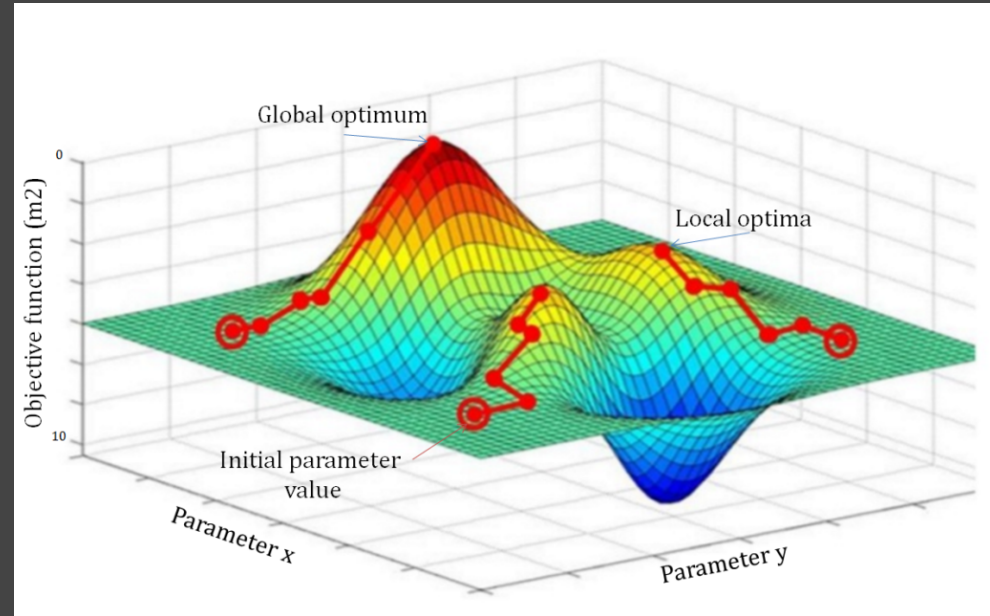
Chooses new foil
xN times

Optimizers



Optimizers

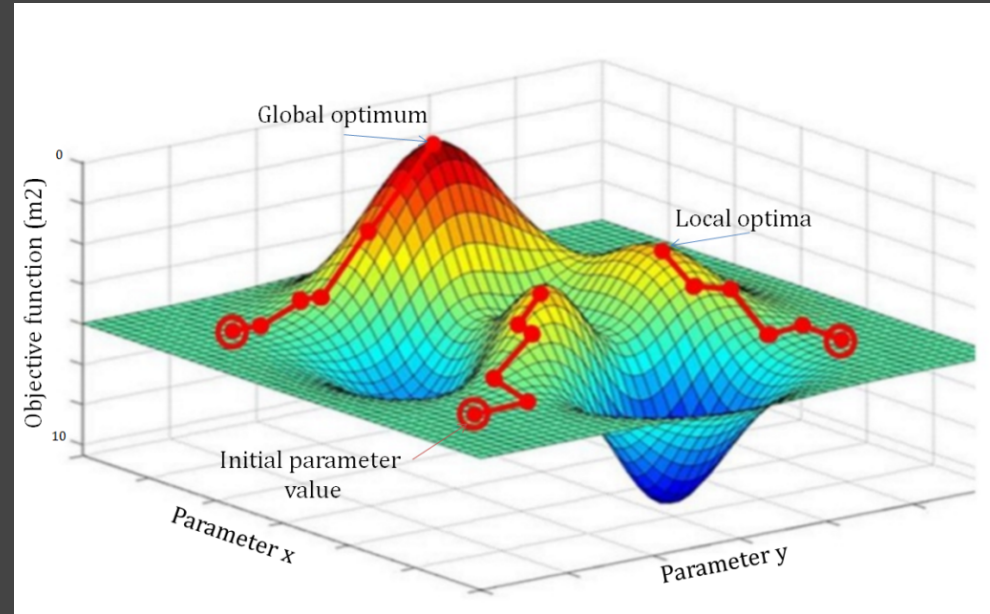
Why use the optimizer this way?



Optimizers

Why use the optimizer this way?

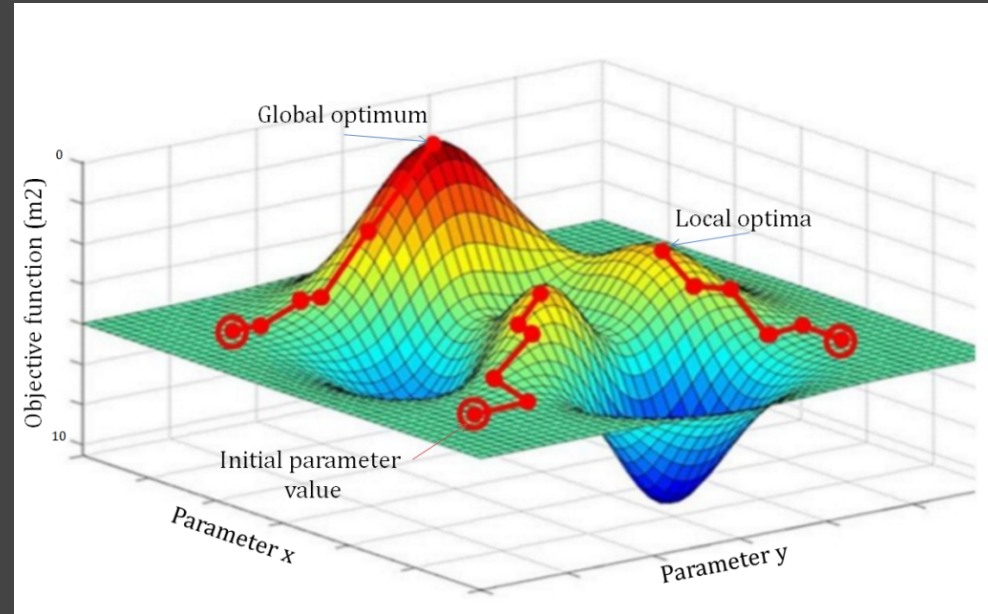
- The global optima might not account for some outside factor



Optimizers

Why use the optimizer this way?

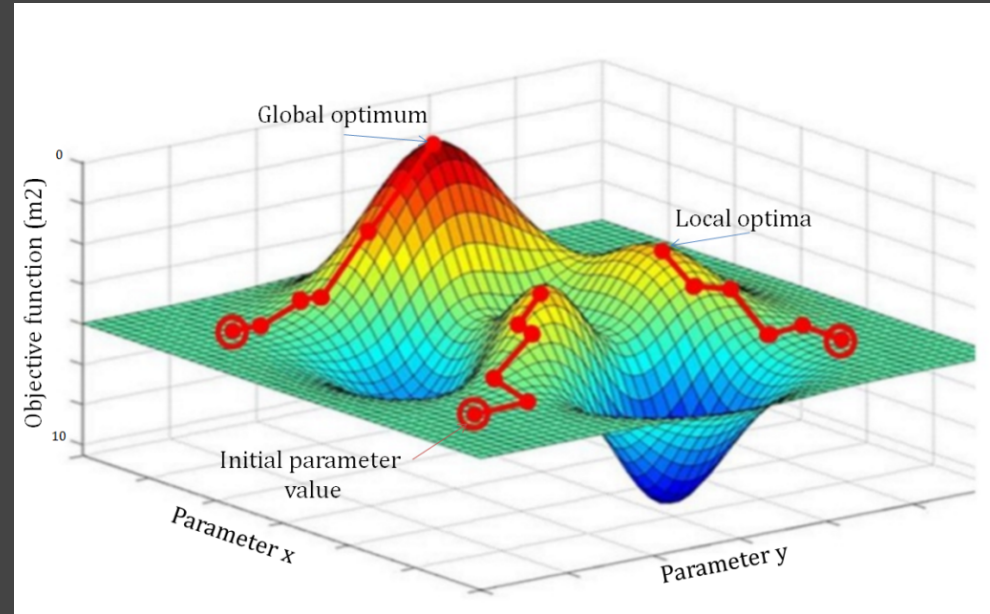
- The global optima might not account for some outside factor
- The optimizer might optimize towards the wrong optima



Optimizers

Why use the optimizer this way?

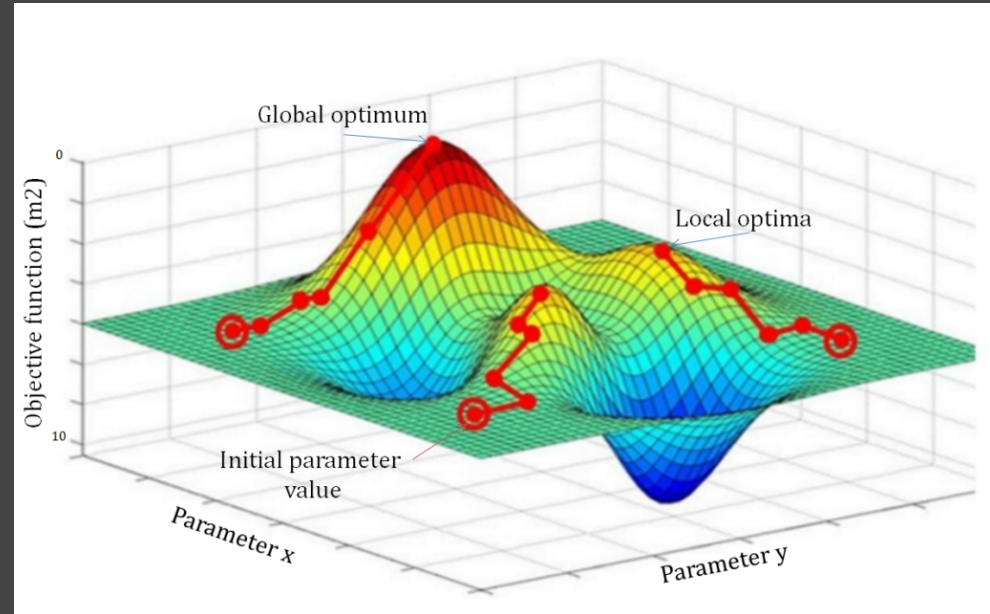
- The global optima might not account for some outside factor
- The optimizer might optimize towards the wrong optima
- Inspiration



Optimizers

Why use the optimizer this way?

- The global optima might not account for some outside factor
- The optimizer might optimize towards the wrong optima
- Inspiration



Illumination

Evolutionary Algorithms

[https://www.youtube.com/embed/bwB6PulBS9A?
enablejsapi=1&mute=1&autoplay=1](https://www.youtube.com/embed/bwB6PulBS9A?enablejsapi=1&mute=1&autoplay=1)

[https://youtu.be/bwB6PulBS9
A](https://youtu.be/bwB6PulBS9A)

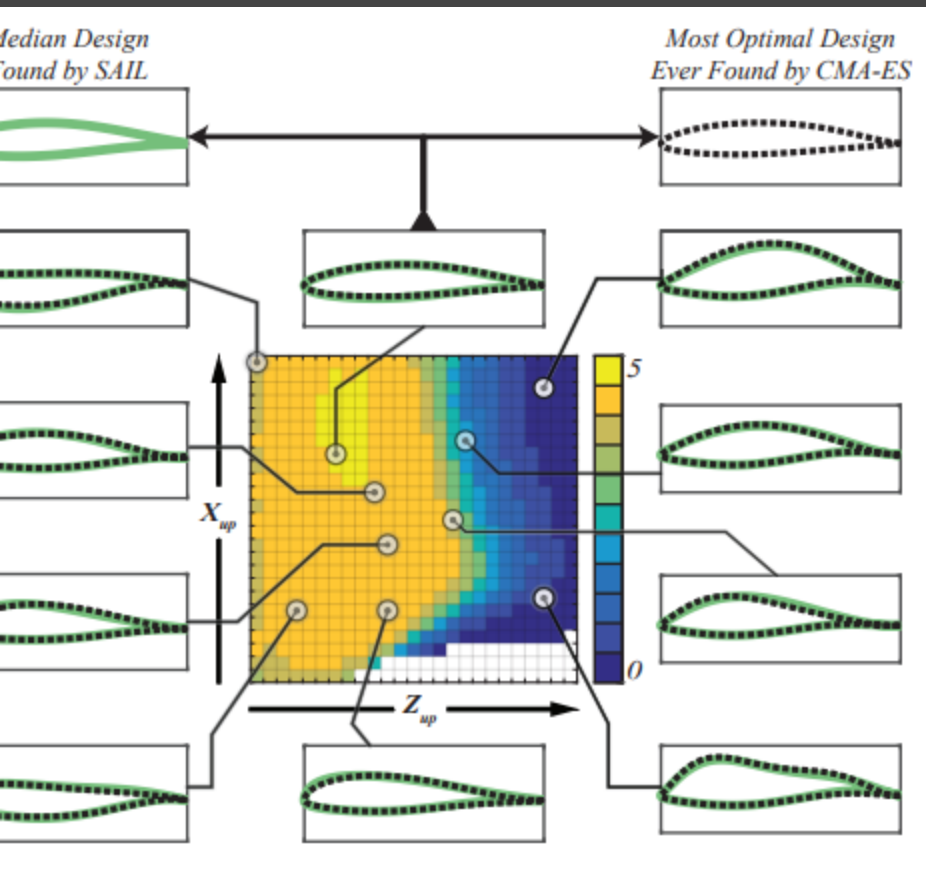
Evolutionary Algorithms

[https://www.youtube.com/embed/ncyFAMrWgWc?
start=90&mute=1&enablejsapi=1](https://www.youtube.com/embed/ncyFAMrWgWc?start=90&mute=1&enablejsapi=1)

<https://youtu.be/bwB6PulBS9>

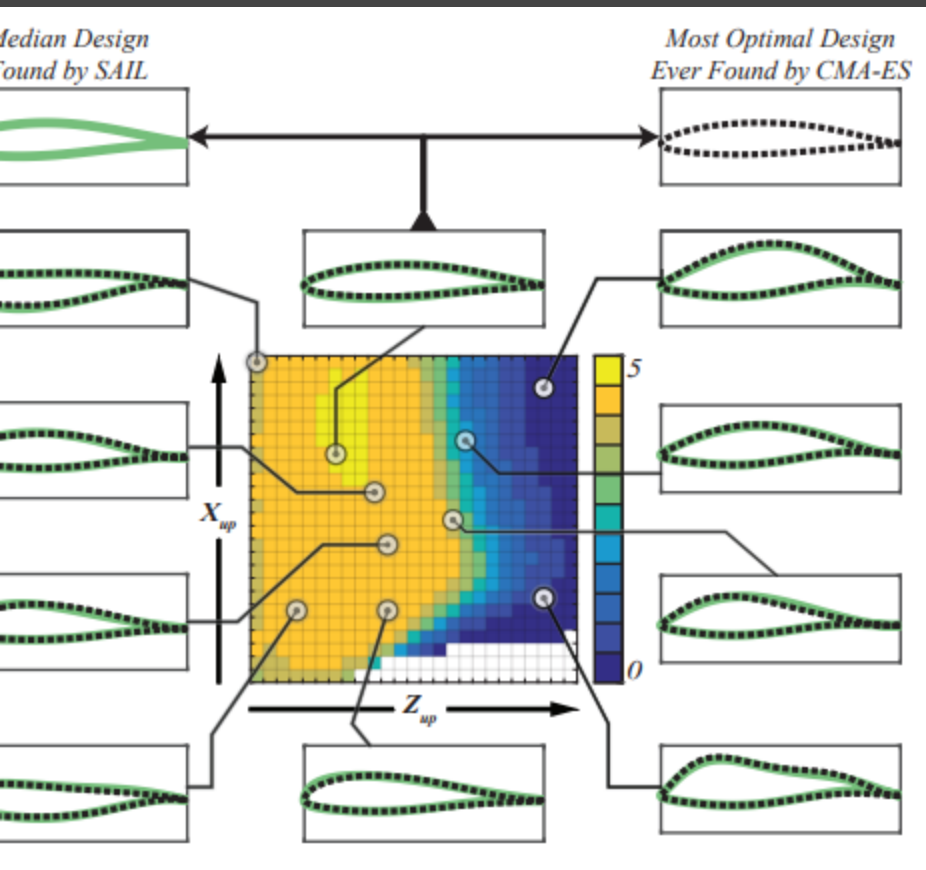
^A
[https://youtu.be/ncyFAMrWgWc?
t=90](https://youtu.be/ncyFAMrWgWc?t=90)

Data-Efficient Design Exploration through Surrogate- Assisted Illumination



SAIL is
designed to:

Data-Efficient Design Exploration through Surrogate- Assisted Illumination

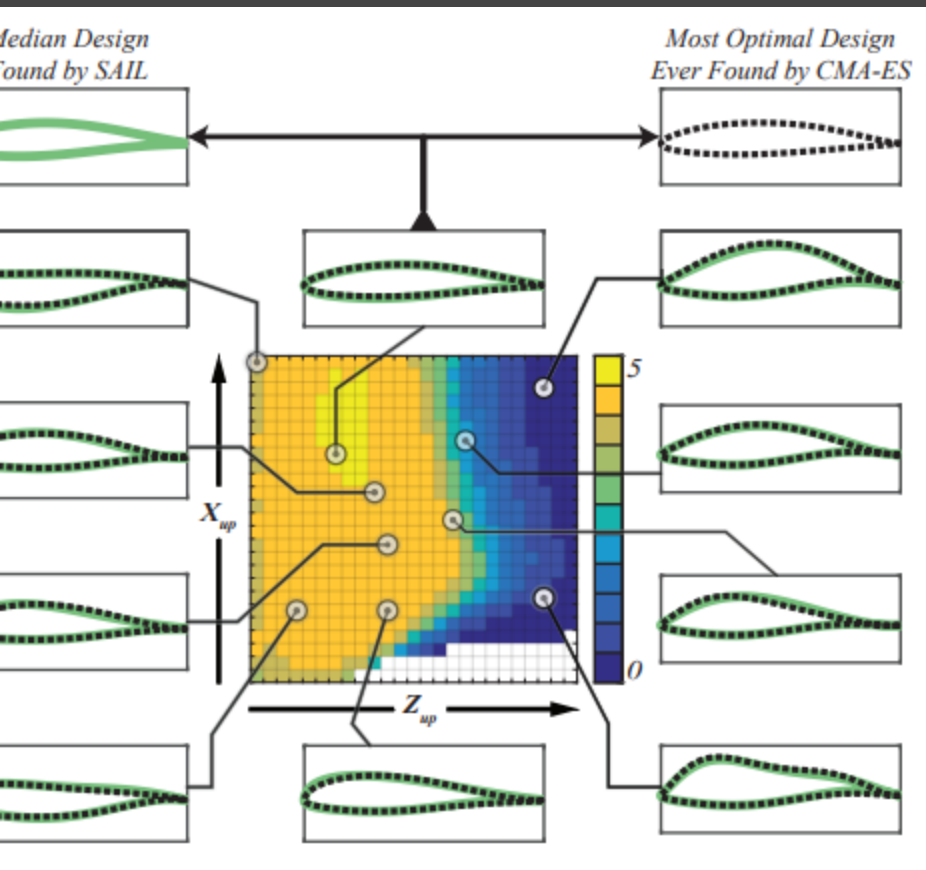


SAIL is
designed to:

- Illuminate the problem space

Data-Efficient Design

Exploration through Surrogate-Assisted Illumination

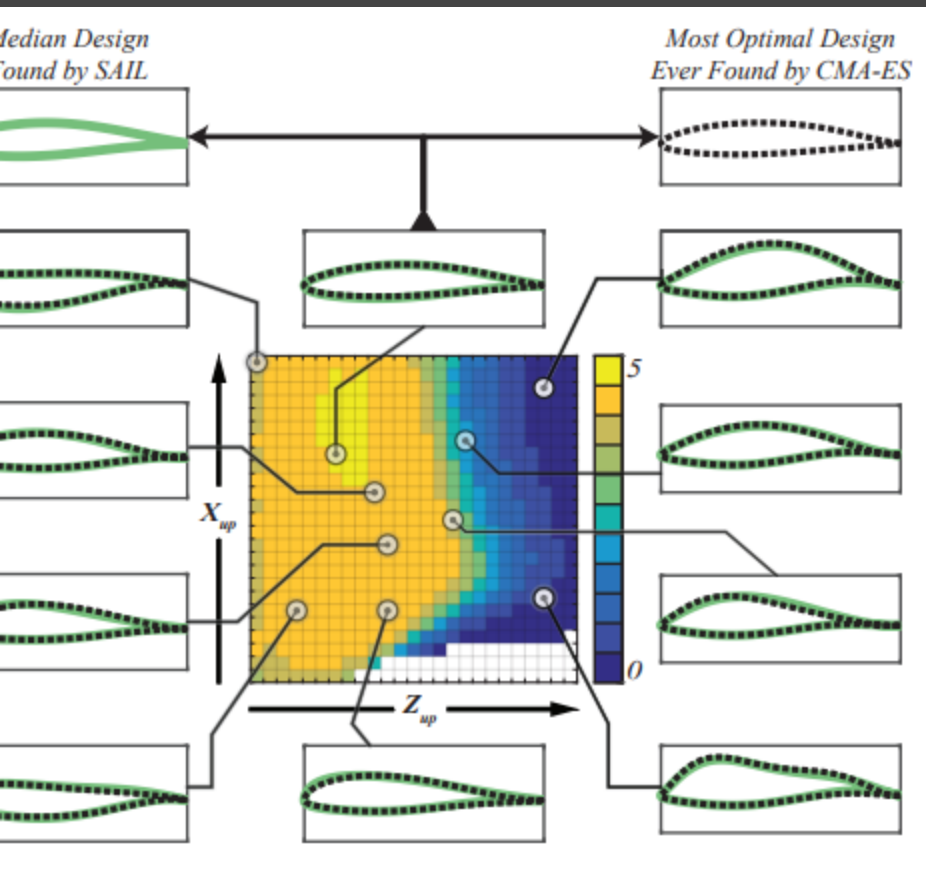


SAIL is designed to:

- Illuminate the problem space
- Be Data Efficient

Data-Efficient Design

Exploration through Surrogate-Assisted Illumination



SAIL is designed to:

- Illuminate the problem space
- Be Data Efficient
- Accurately model the underlying function

SAIL

SAIL

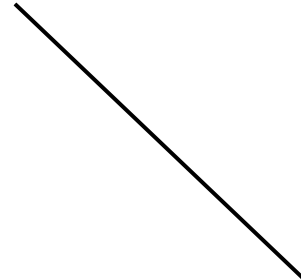
MAP-Elites
For Illumination

**Bayesian
Optimization**

Quality Control of
Gaussian Process

**Gaussian
Processes**

To model problem
space



SAIL

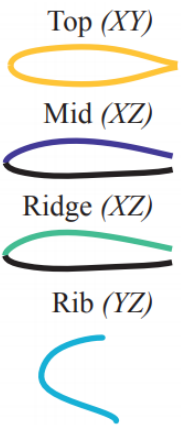
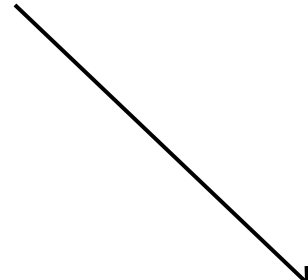
Bayesian Optimization

Quality Control of
Gaussian Process

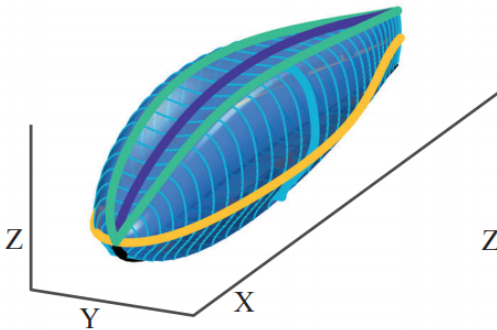
MAP-Elites For Illumination

Gaussian Processes

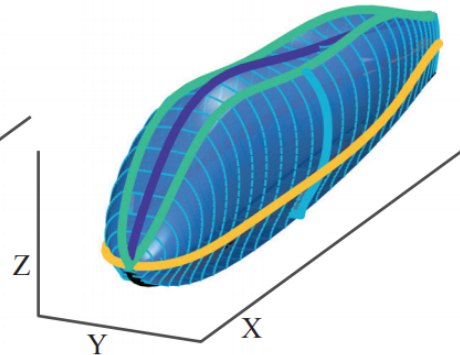
To model problem
space



Middle Parameter Values

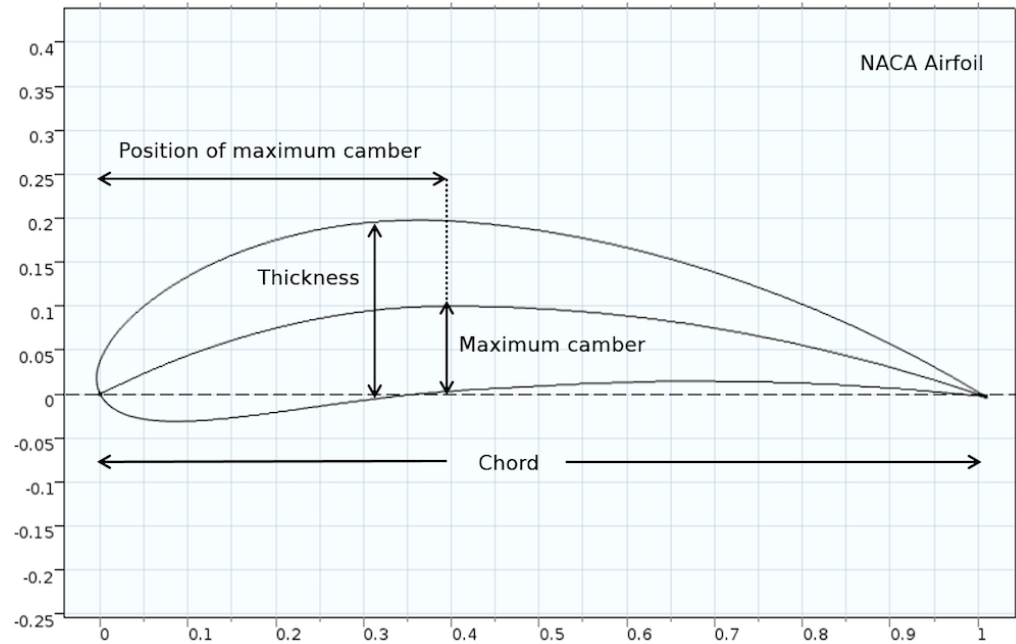
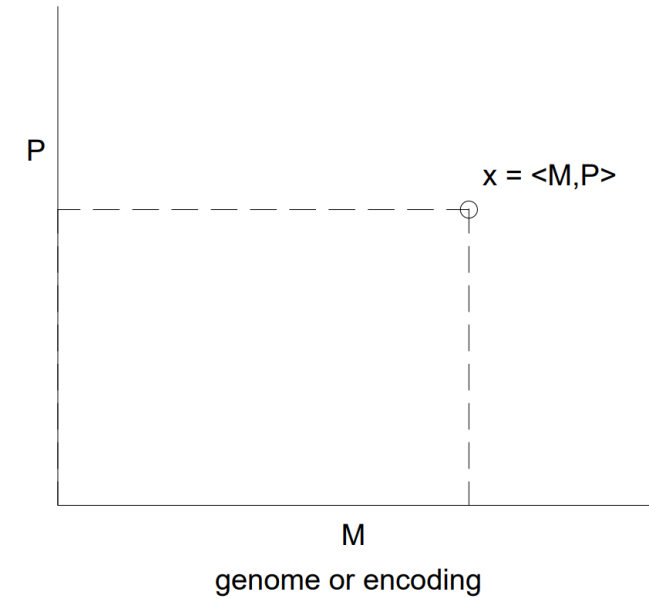


Random Parameter Values



Taken from [1]

MAP-Elites Illumination

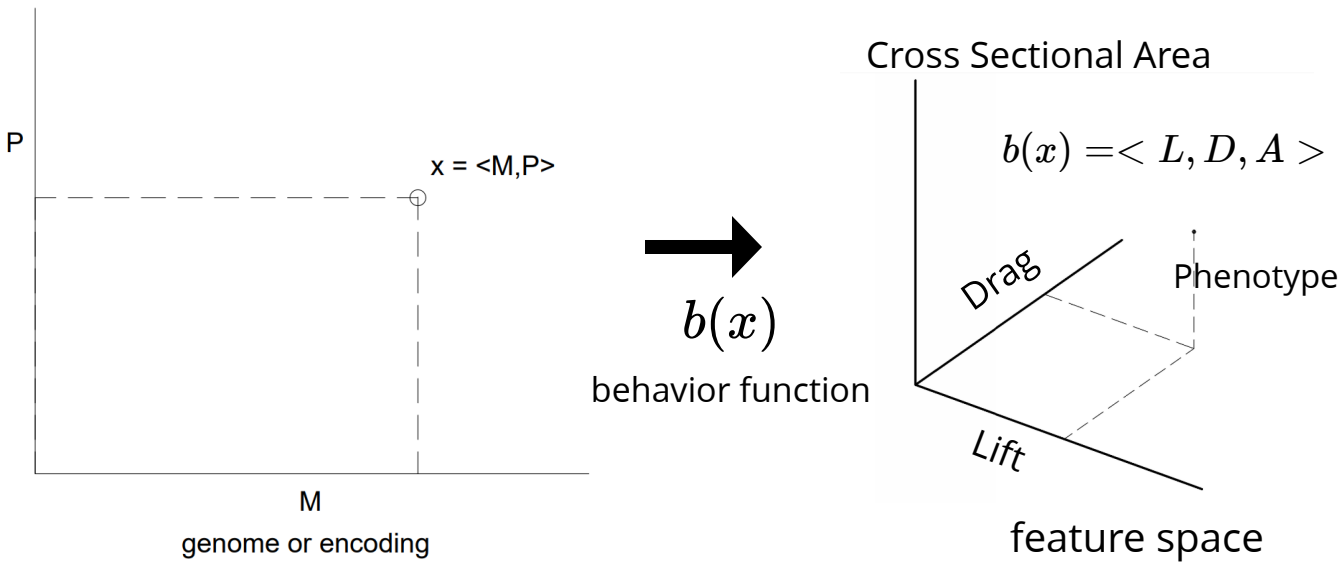


<https://www.comsol.com/blogs/optimize-naca-airfoil-designs-with-a-simulation-app/>

Genomes

How we express a physical object in a compact form

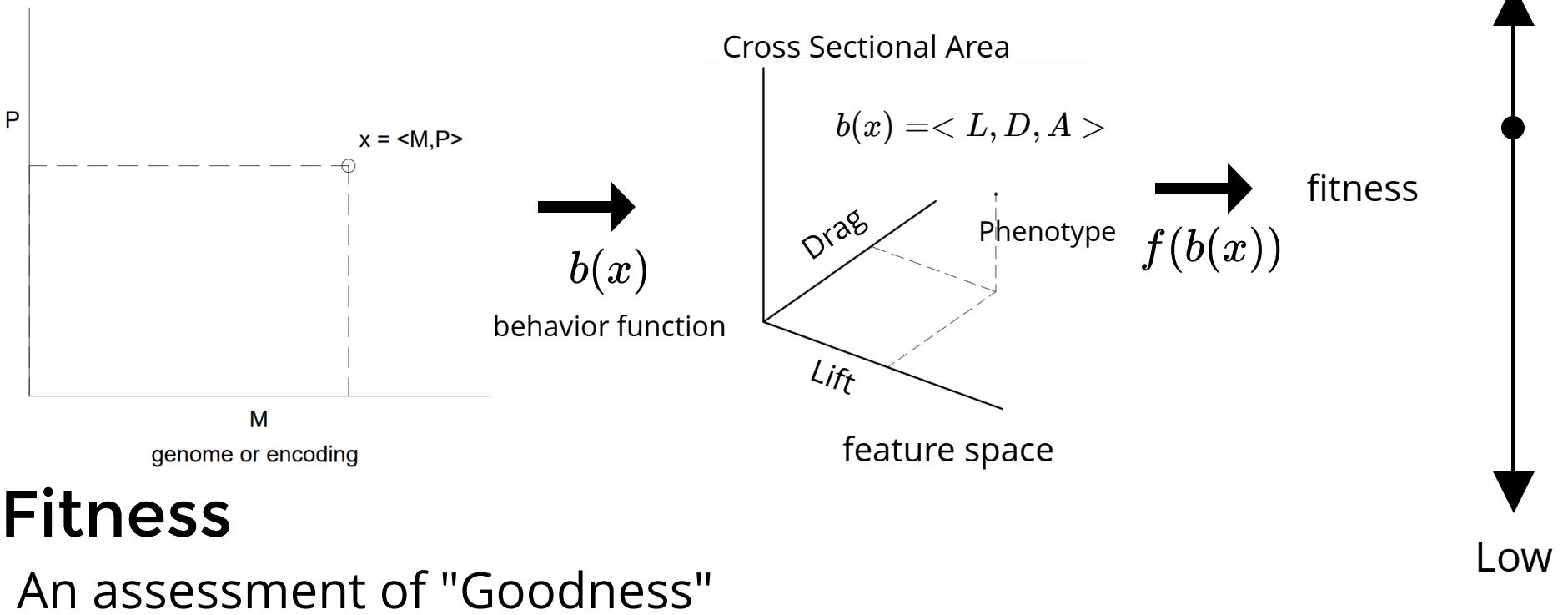
MAP-Elites Illumination



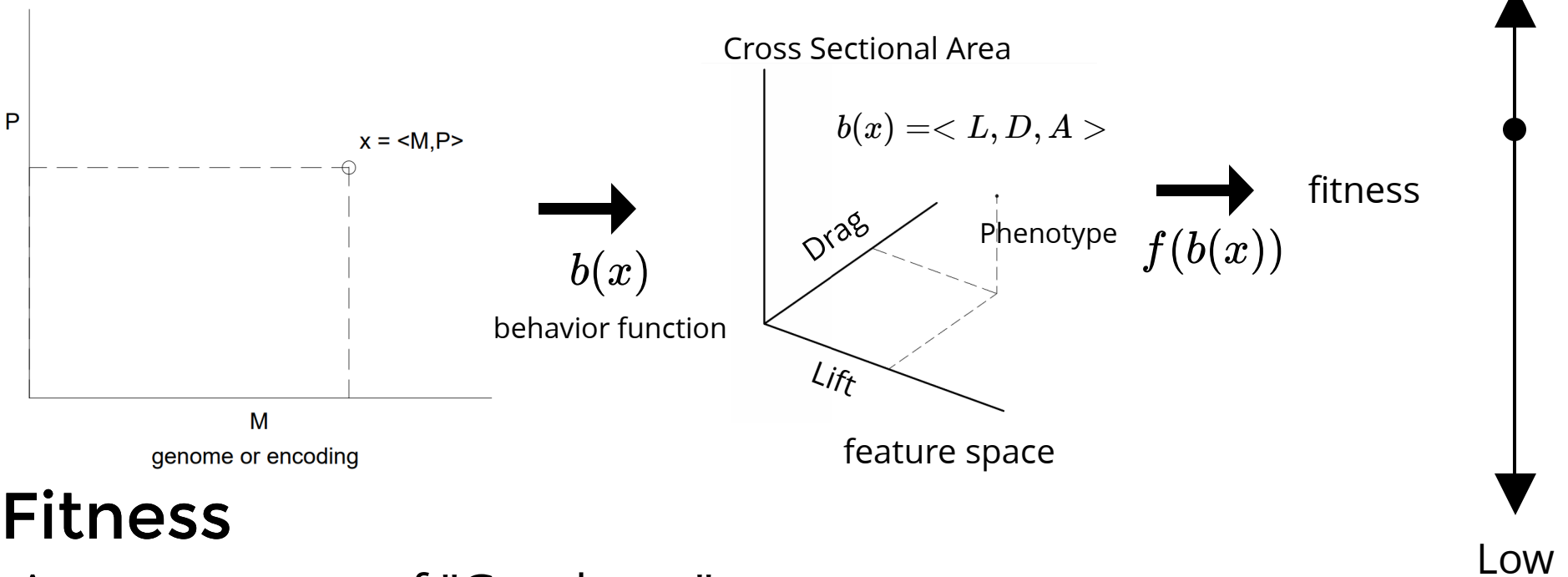
Phenotypes

The characteristics of an individual

MAP-Elites Illumination



MAP-Elites Illumination

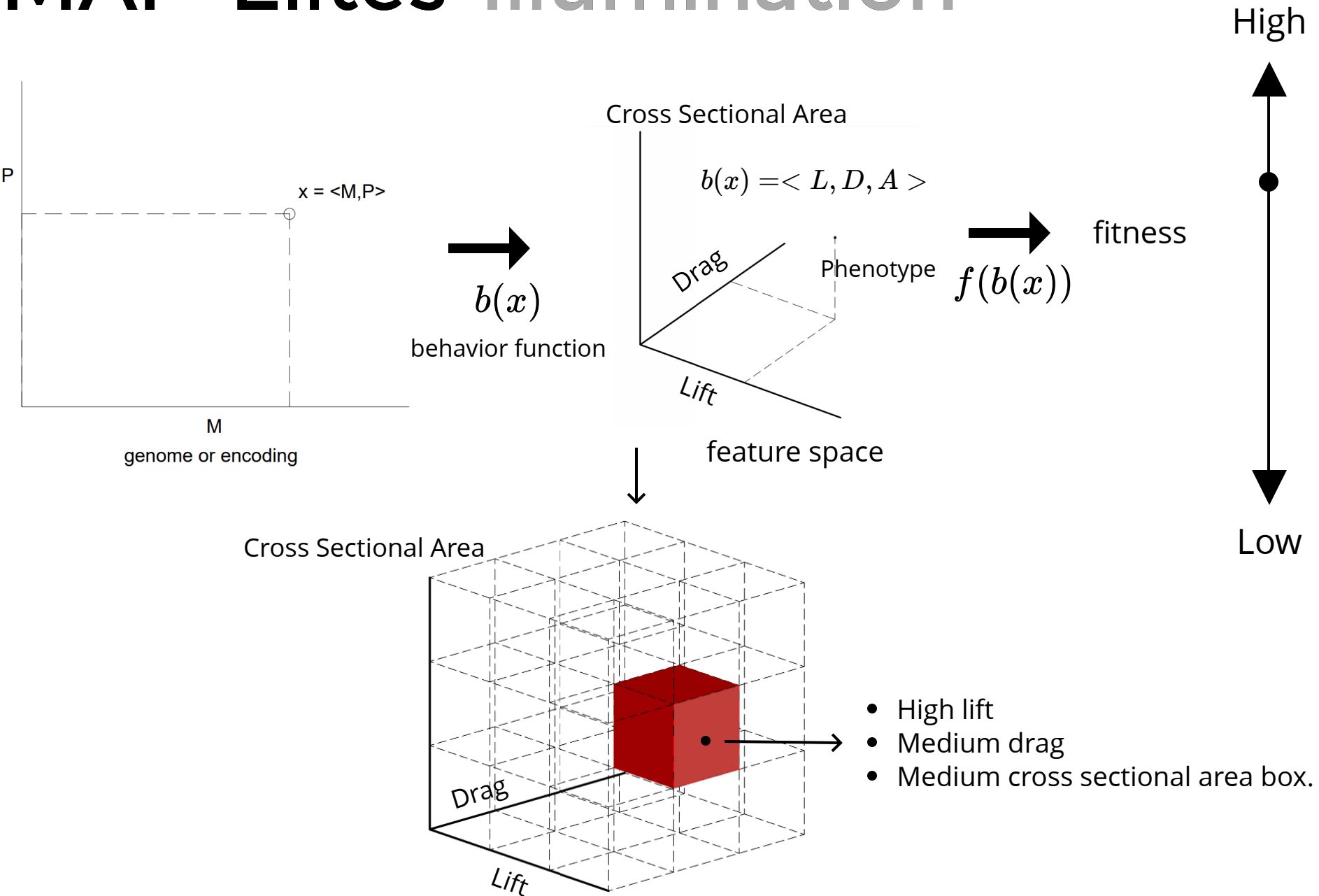


Fitness

An assessment of "Goodness"

$$f(x) = Lift(x) - b * Drag(x) + c * Area(x)$$

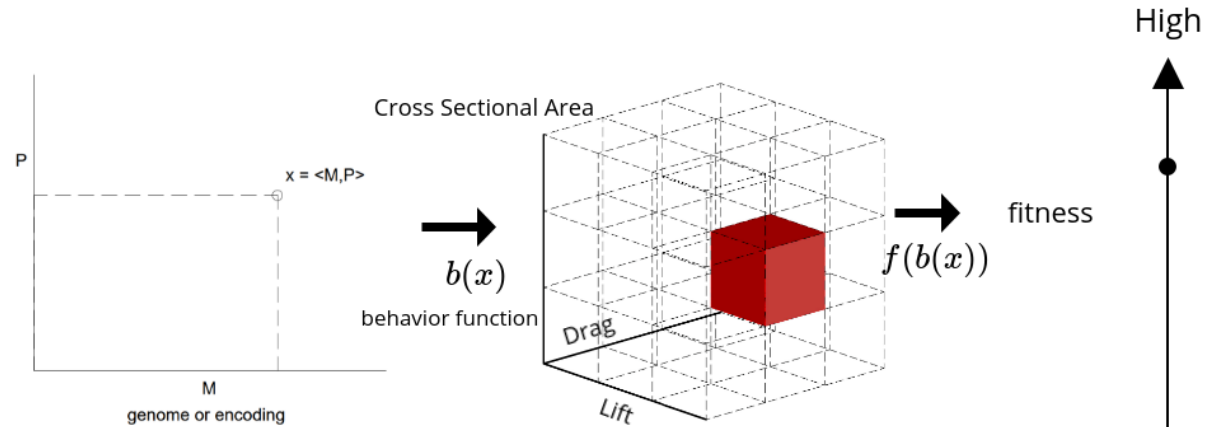
MAP-Elites Illumination



MAP-Elites Illumination

MAP-Elites Illumination

Setup



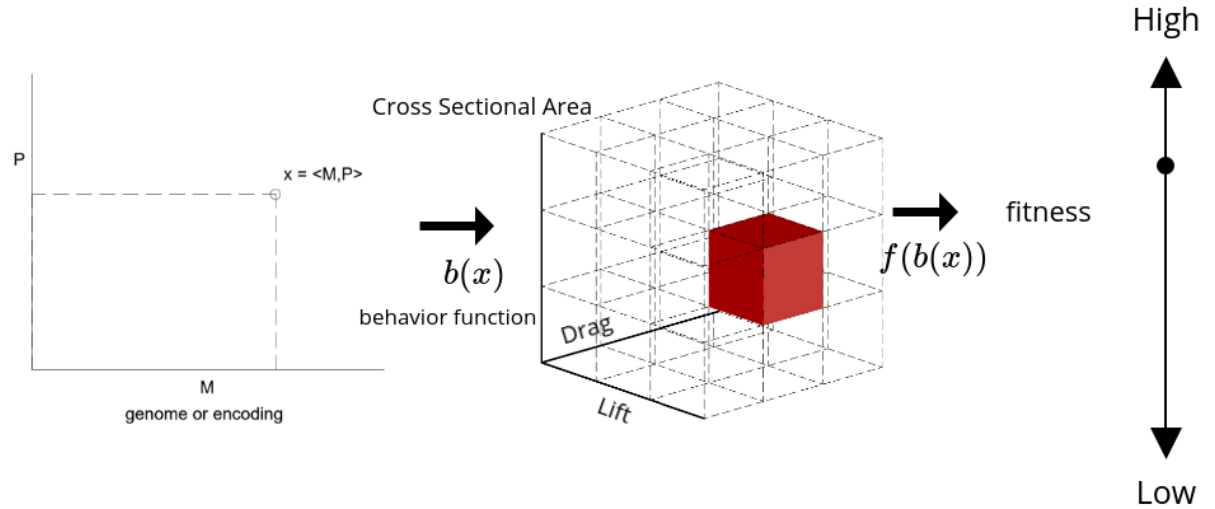
Evolution

Termination

MAP-Elites Illumination

Setup

- Create random set of solutions, X



Evolution

Termination

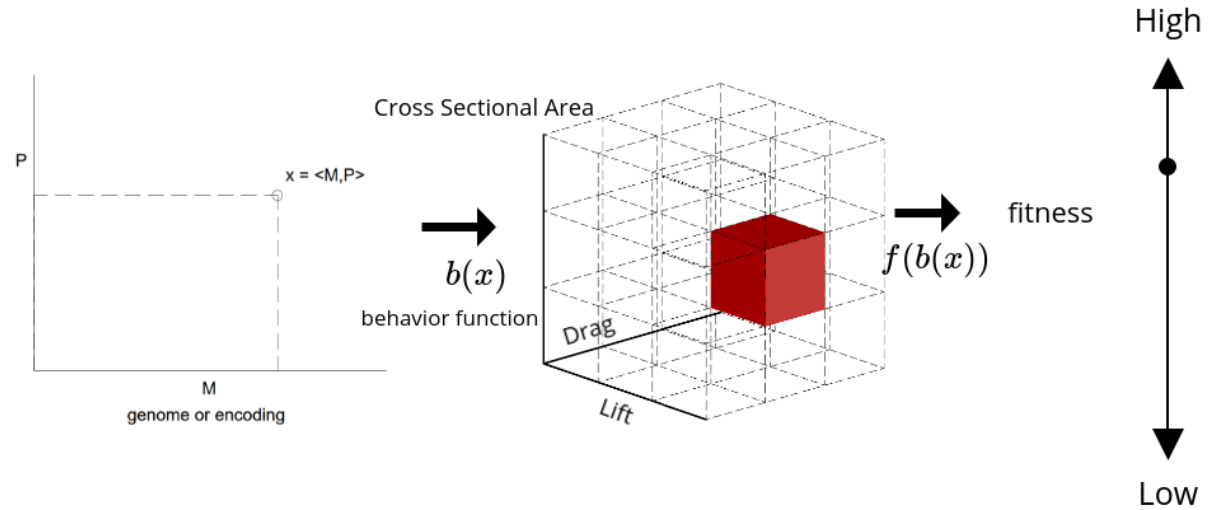
MAP-Elites Illumination

Setup

- Create random set of solutions, X
- Add them to the feature space

Evolution

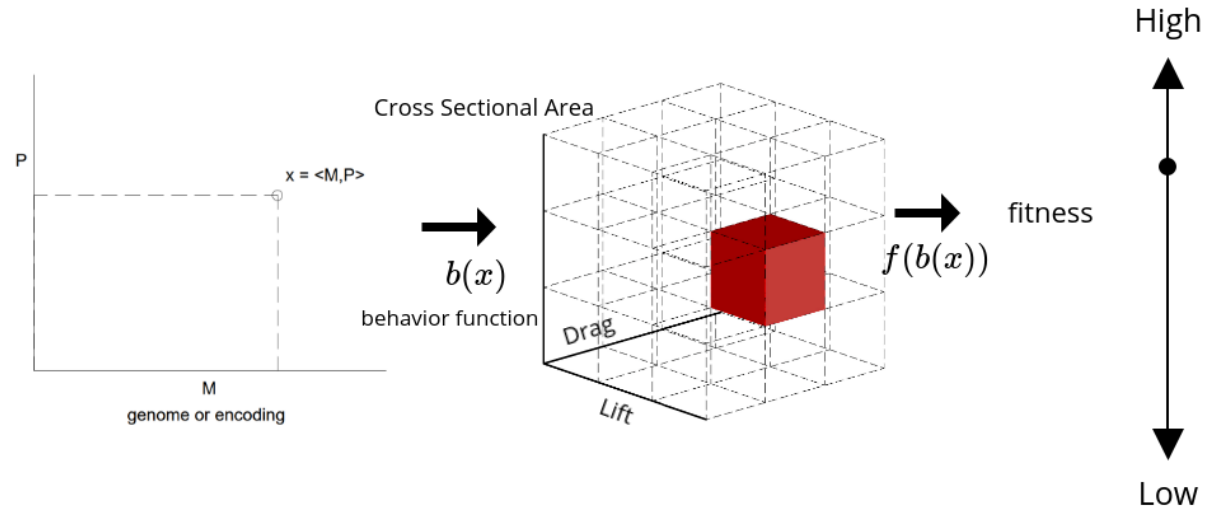
Termination



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Evolution

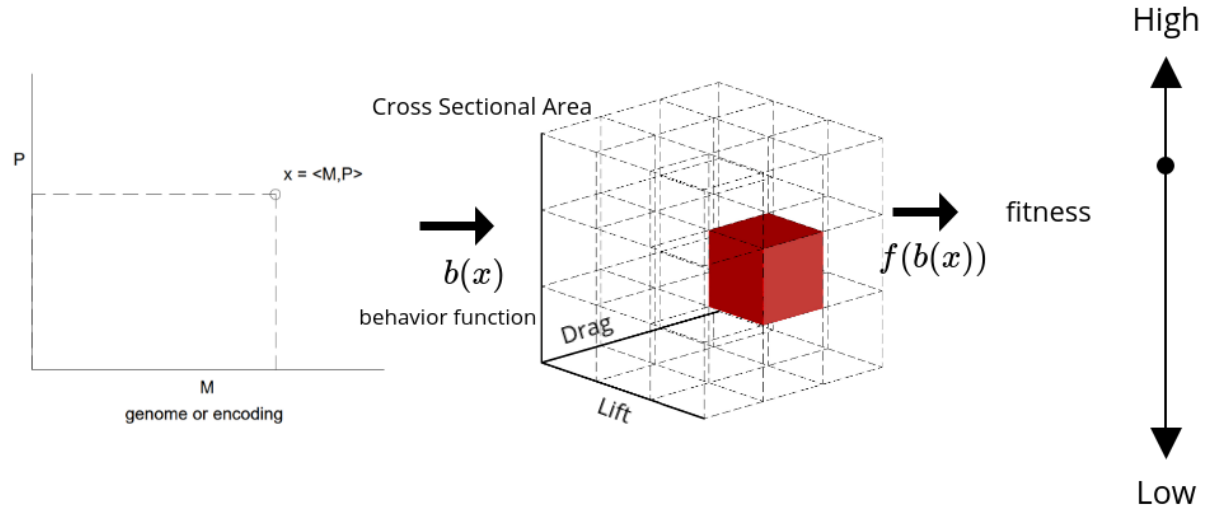
Feature Space Outcomes

Termination

MAP-Elites Illumination

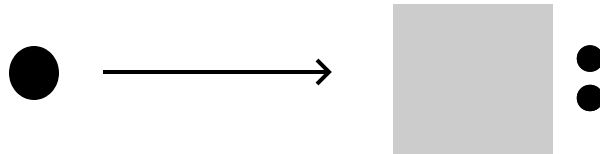
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Evolution

Feature Space Outcomes

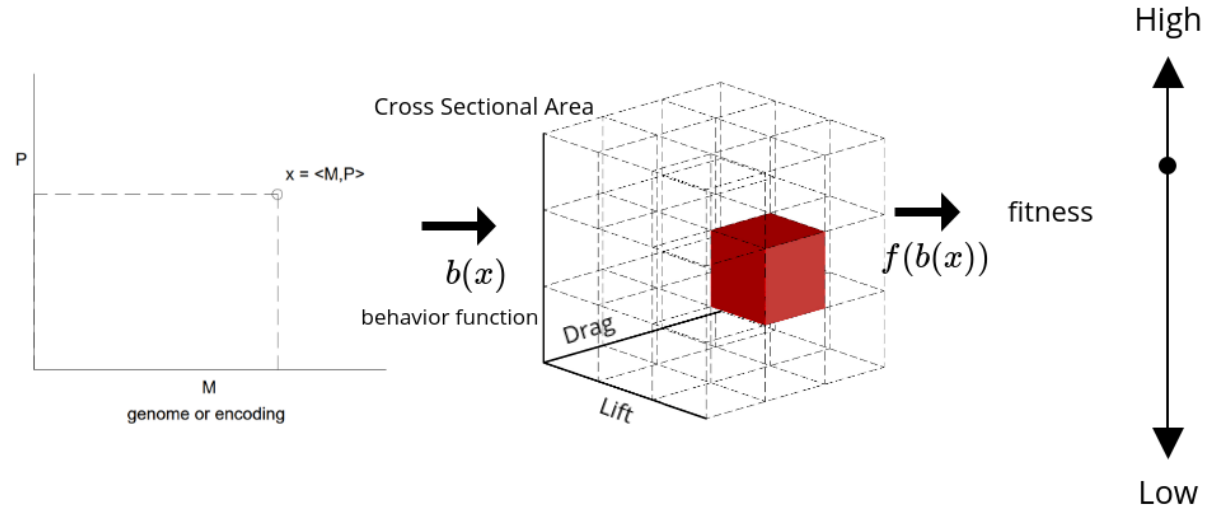


Termination

MAP-Elites Illumination

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Evolution

Feature Space Outcomes

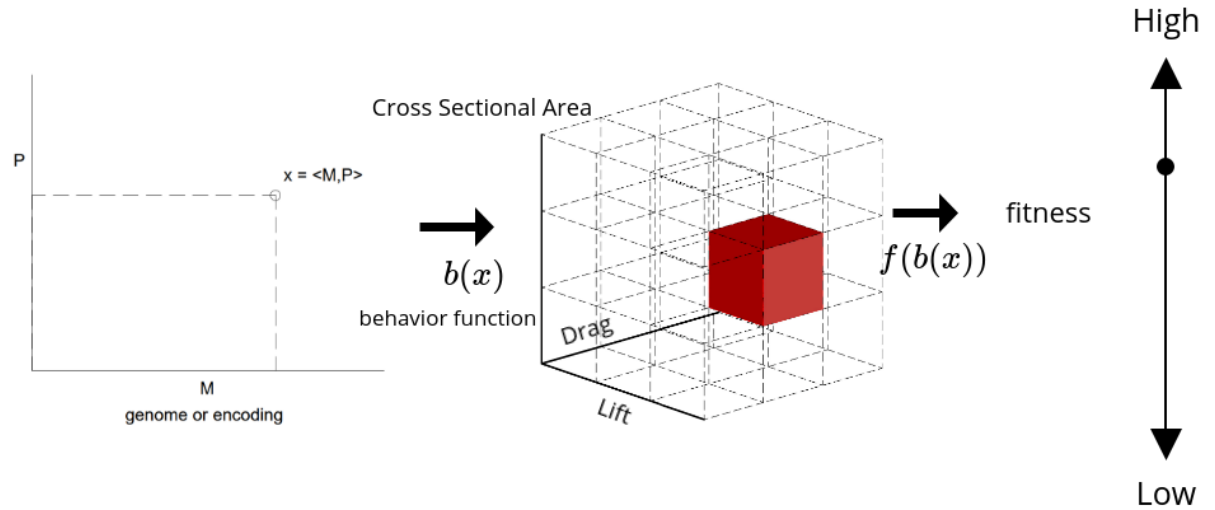


Termination

MAP-Elites Illumination

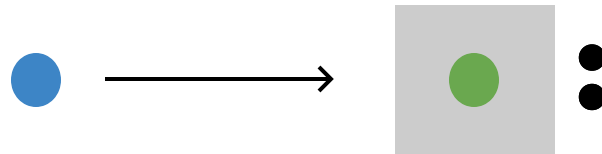
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Evolution

Feature Space Outcomes



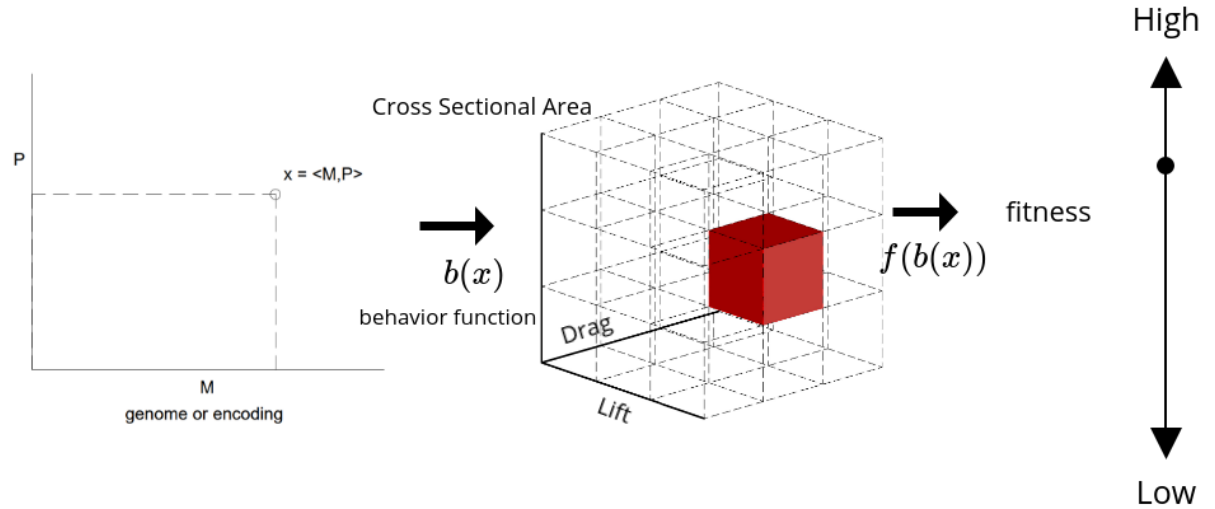
$$F(\text{blue circle}) \leq F(\text{green circle})$$

Termination

MAP-Elites Illumination

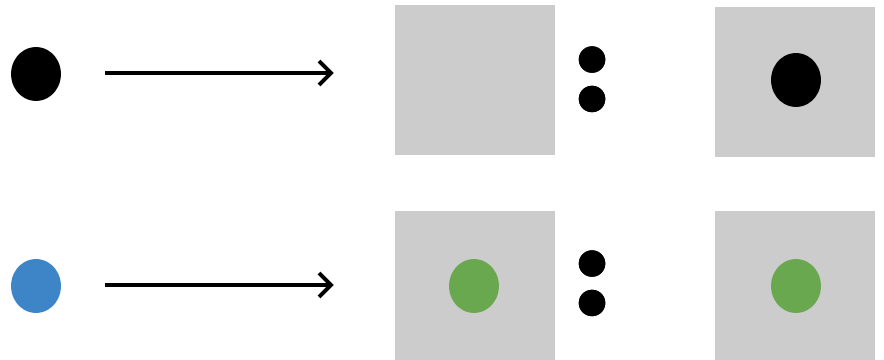
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Evolution

Feature Space Outcomes



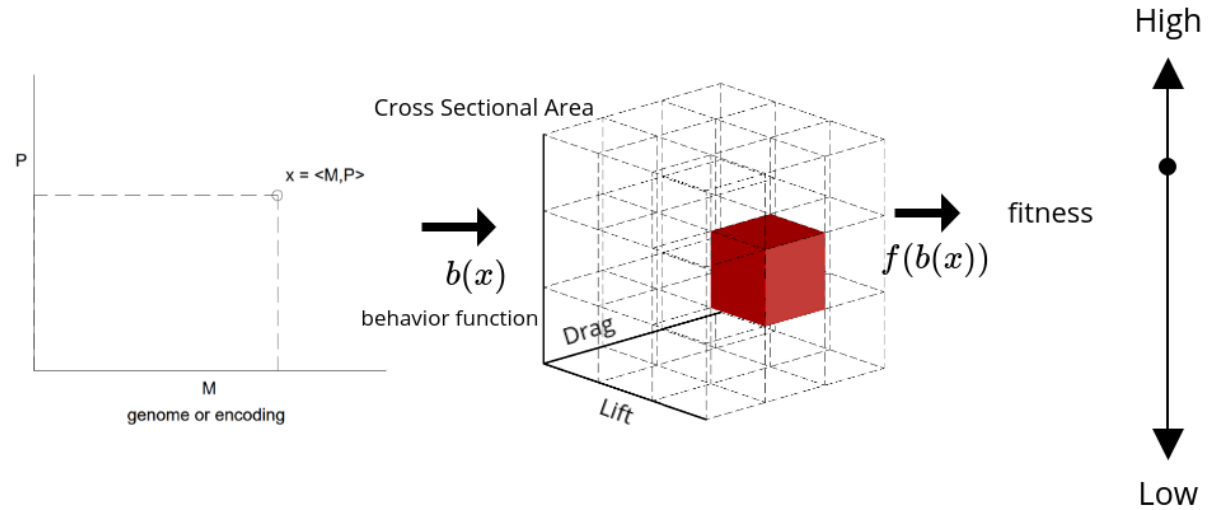
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Termination

MAP-Elites Illumination

Setup

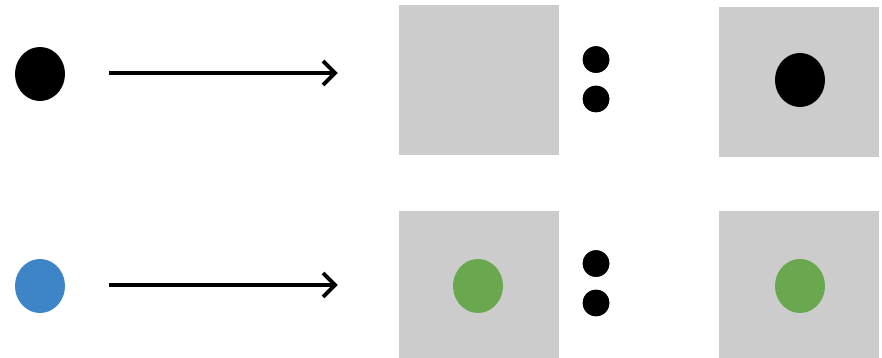
- Create random set of solutions, X
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Evolution

```
1 for generation in I
2   x ← random_individual(X)
3   x' ← random_variation(x)
4   b' ← behavior_function(x')
5   feature_space_insert(x', b')
```

Feature Space Outcomes



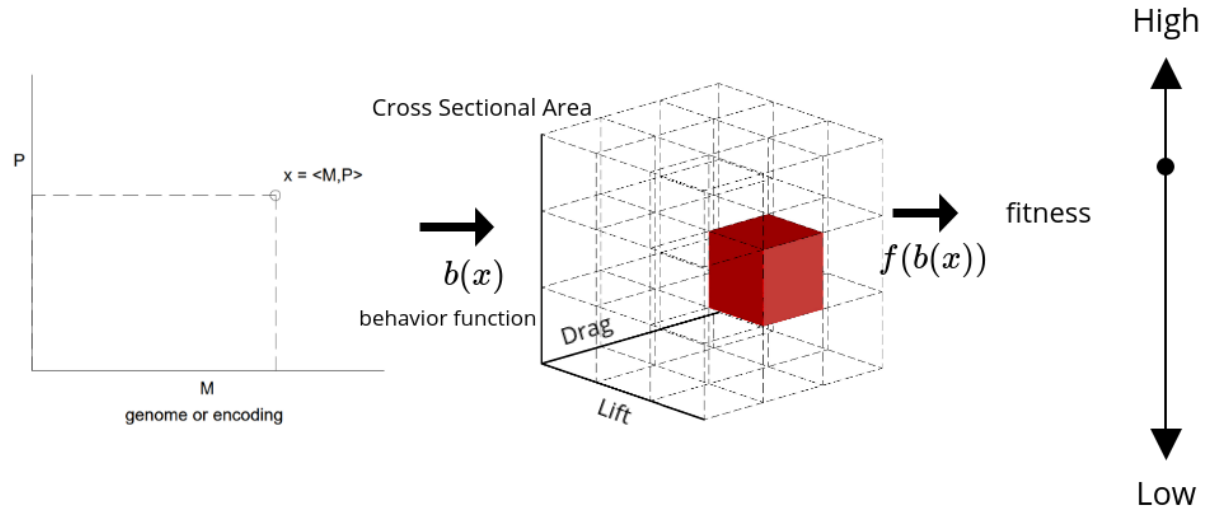
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Termination

MAP-Elites Illumination

Setup

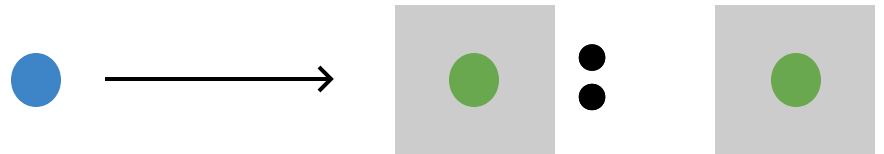
- Create random set of solutions, X
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Feature Space Outcomes



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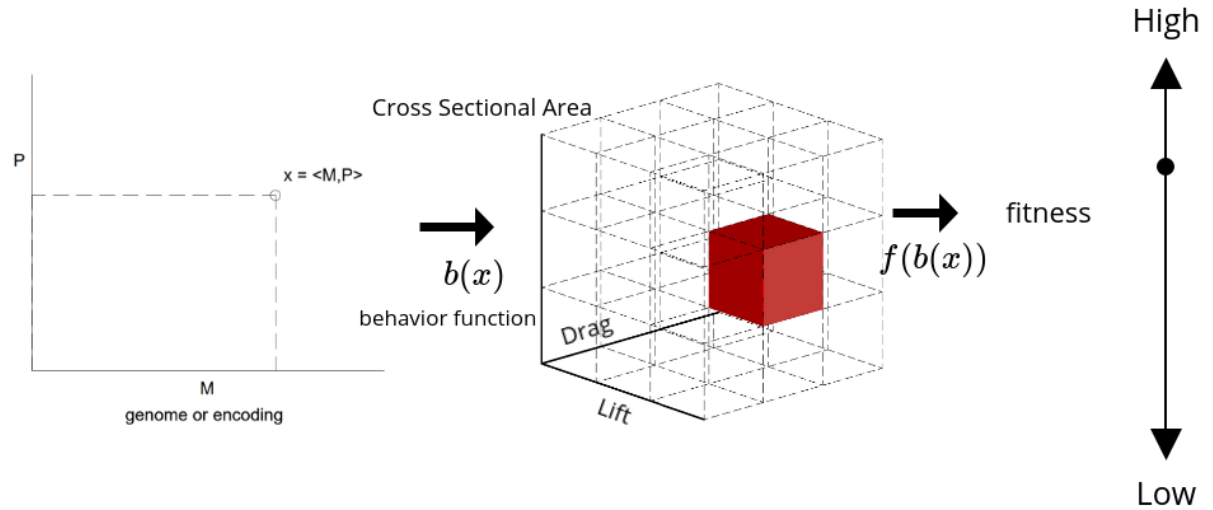
Termination

- Termination condition is reached

MAP-Elites Illumination

Setup

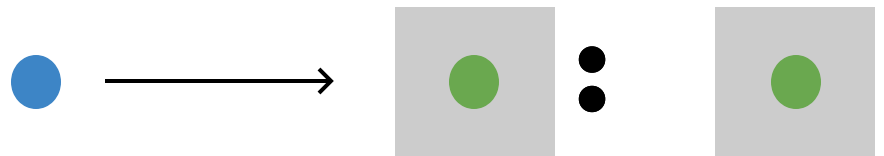
- Create random set of solutions, X
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```

Feature Space Outcomes



$$F(\text{blue circle}) \leq F(\text{green circle})$$

Termination

- Termination condition is reached
- Return individuals and behaviors

Why not just use MAP-Elites?

Why not just use MAP-Elites?

Why not just use MAP-Elites?

It runs the model a lot

Gaussian Processes

Gaussian Processes

- Can make extrapolations with little data

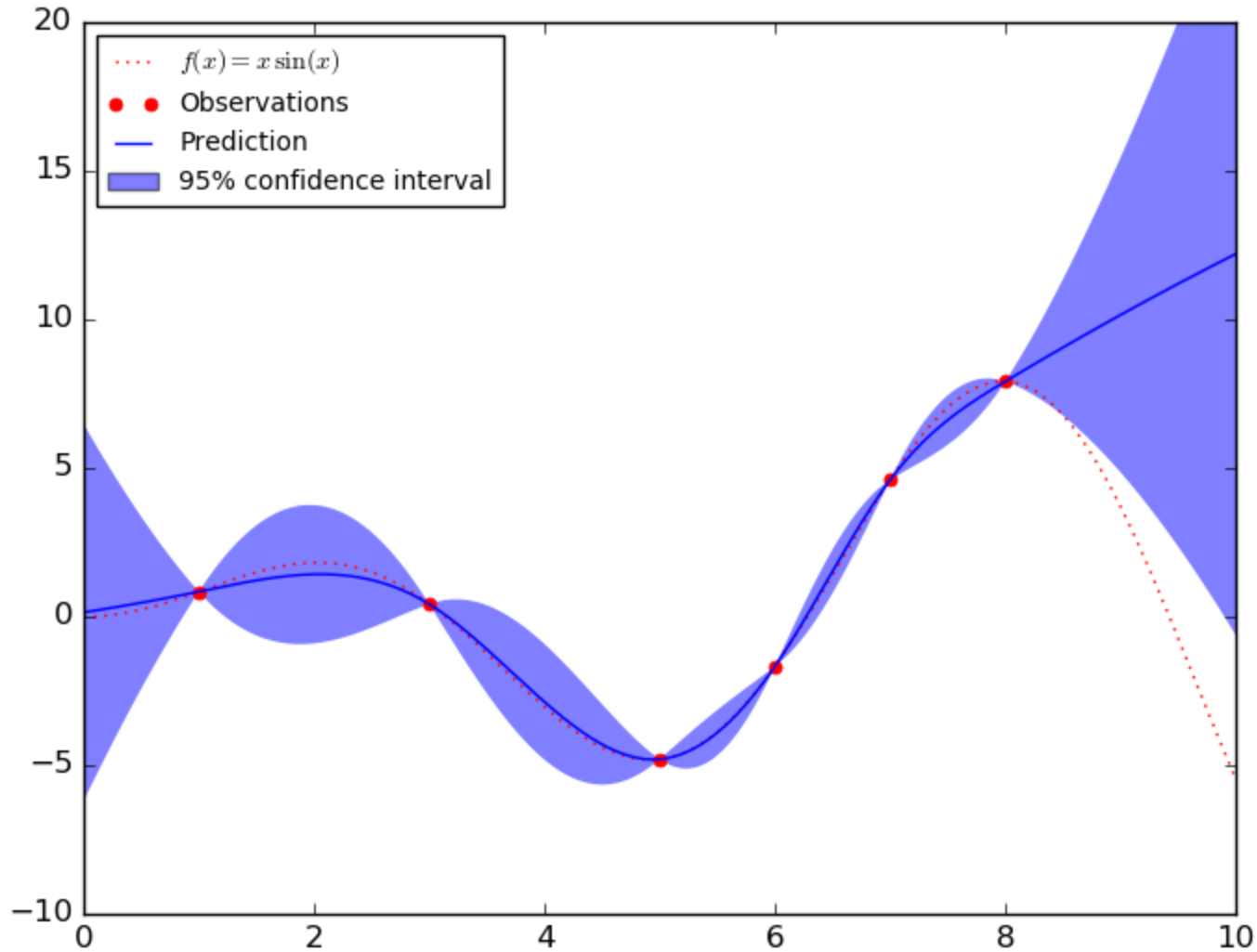
Gaussian Processes

- Can make extrapolations with little data
- Extrapolating points is computationally cheap

Gaussian Processes

- Can make extrapolations with little data
- Extrapolating points is computationally cheap
- Includes a confidence with each extrapolation

Gaussian Processes

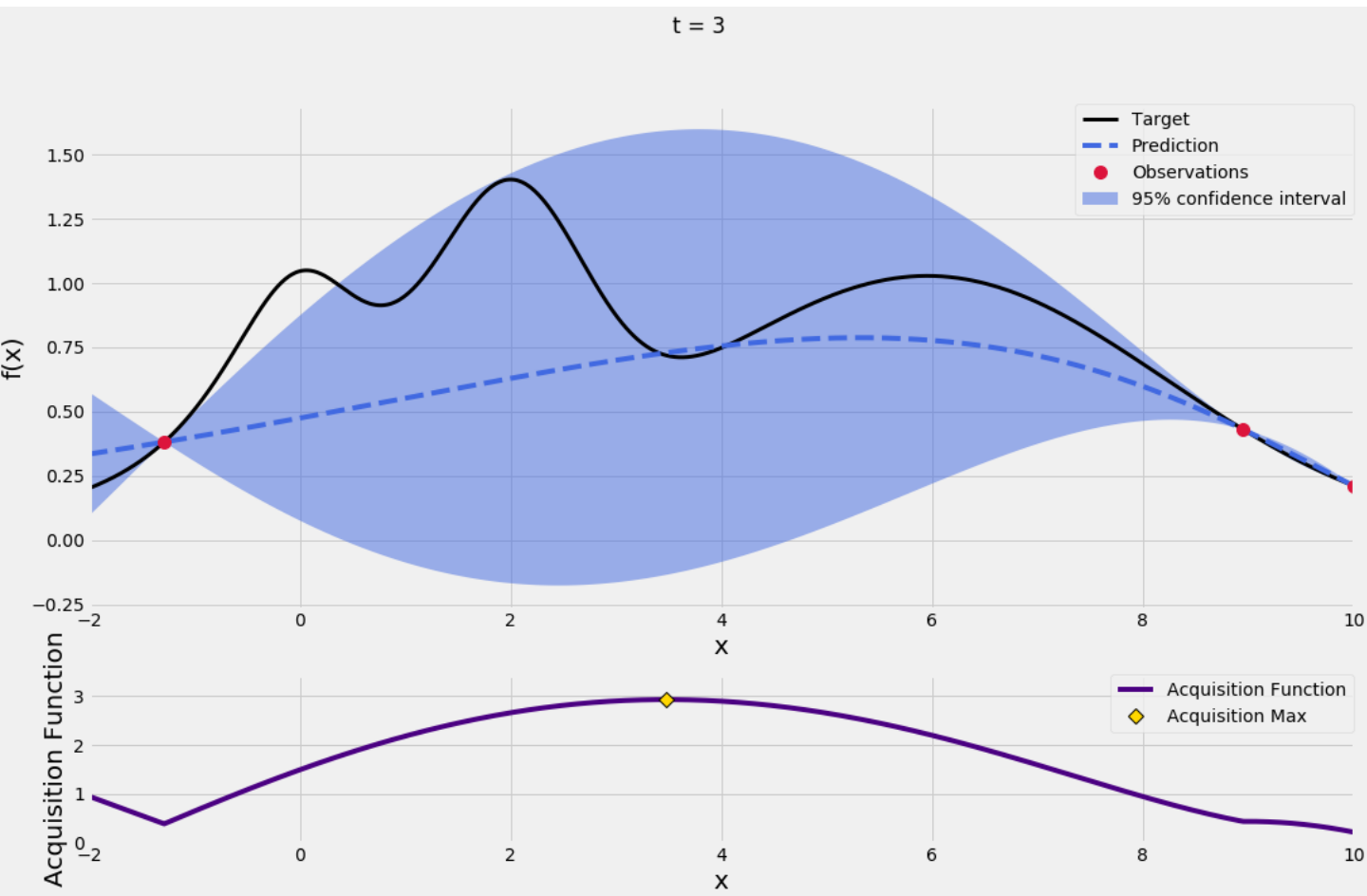


https://scikit-learn.org/0.17/modules/gaussian_process.html

Bayesian Optimization

Upper Confidence Bound:

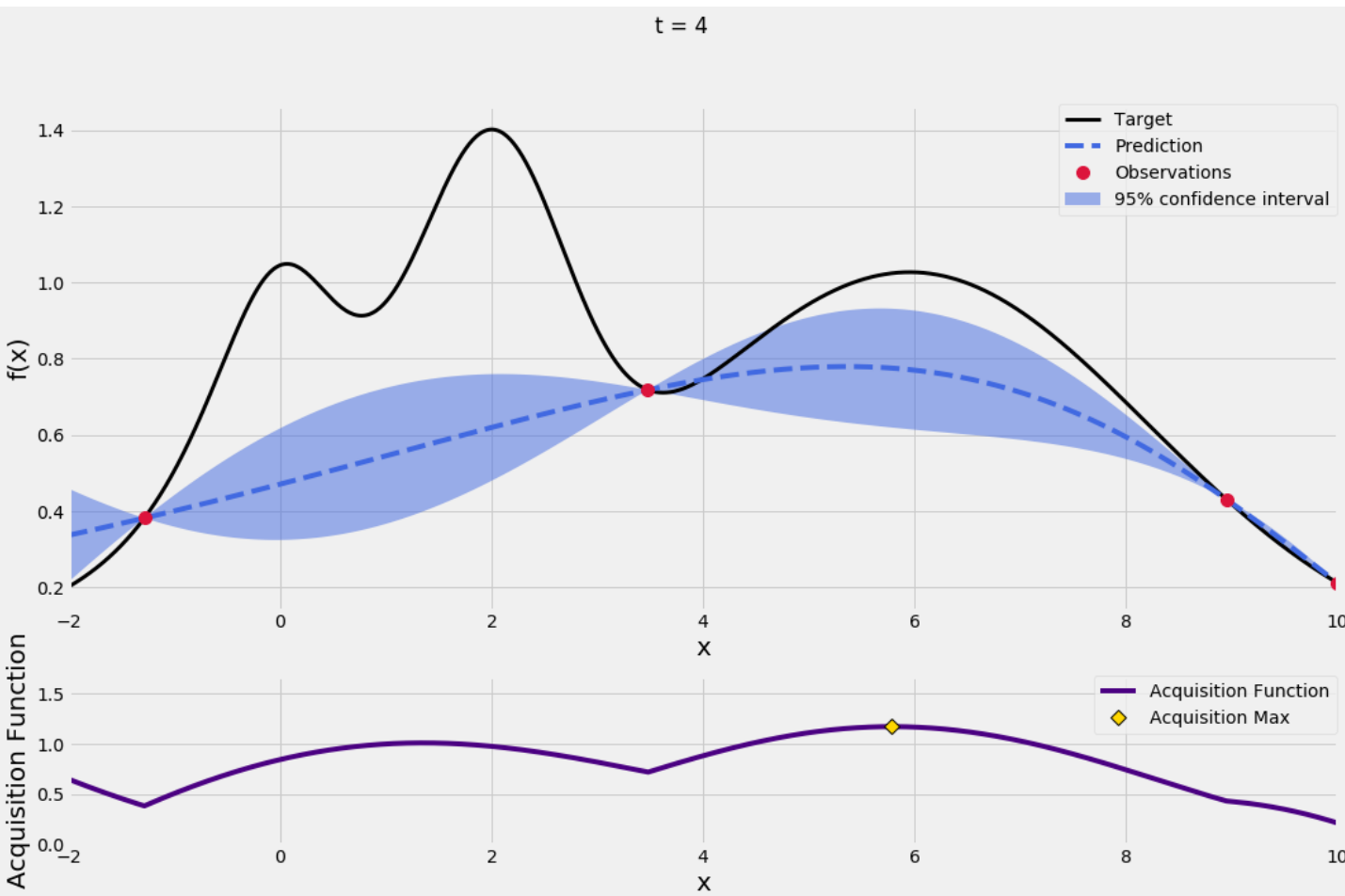
$$UCB(x) = \mu(x) + k\sigma(x)$$



Bayesian Optimization

Upper Confidence Bound:

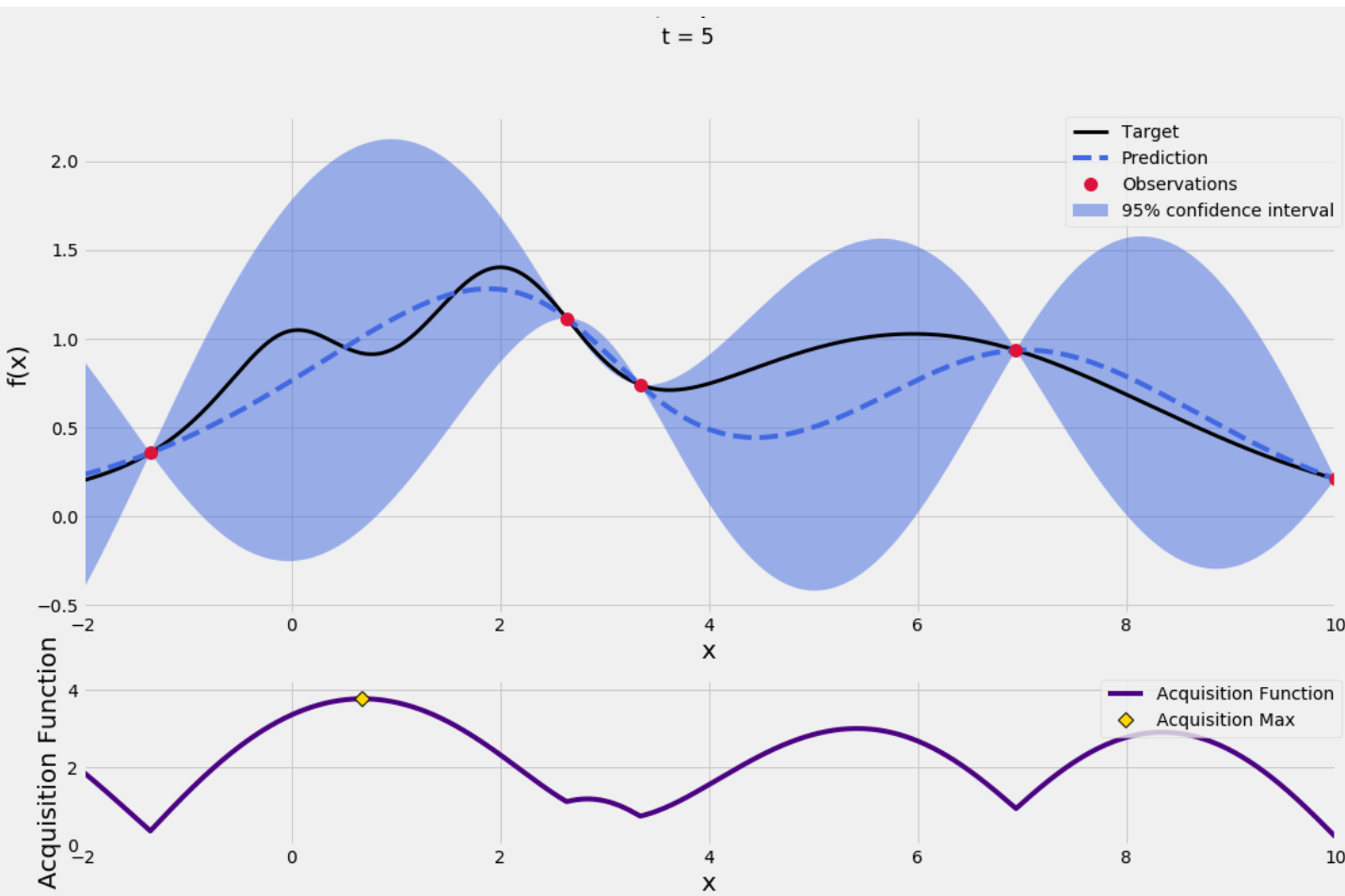
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Bayesian Optimization

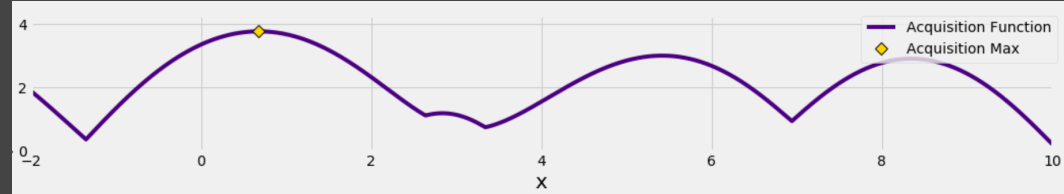
Upper Confidence Bound:

$$UCB(x) = \mu(x) + k\sigma(x)$$



Model Recap

Acquisition Function

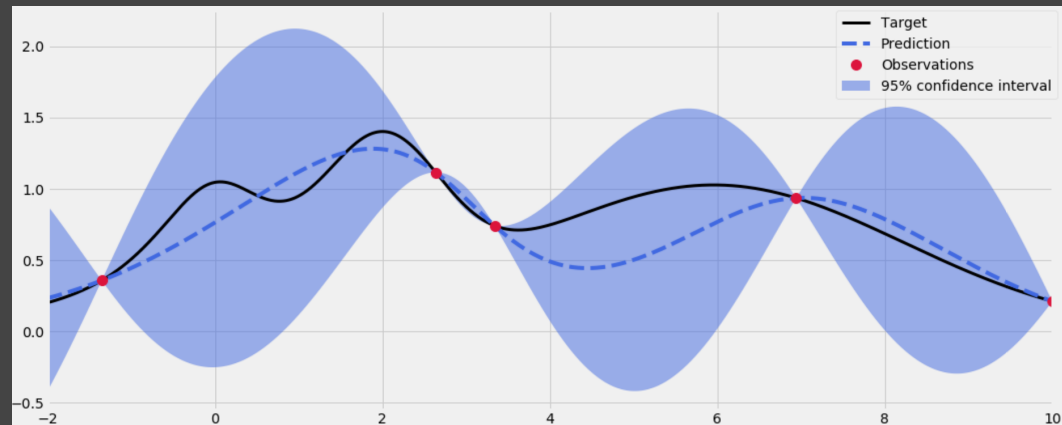
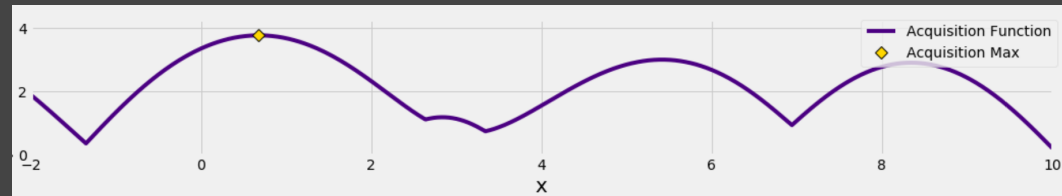


Model Recap

Acquisition Function



Gaussian Process



Model Recap

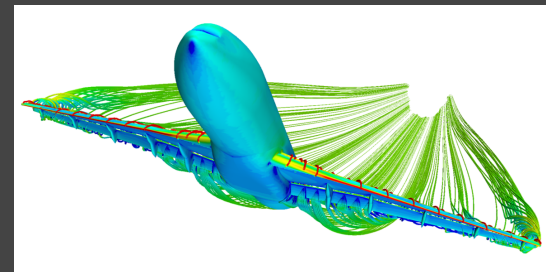
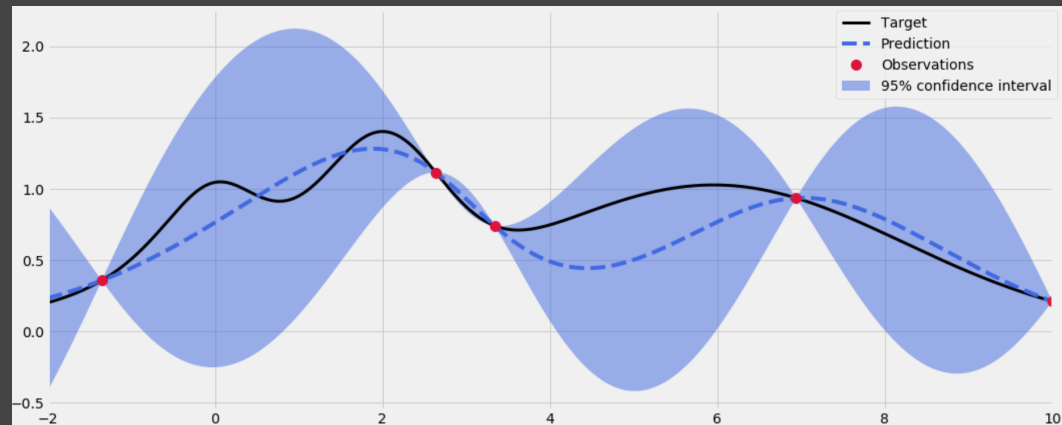
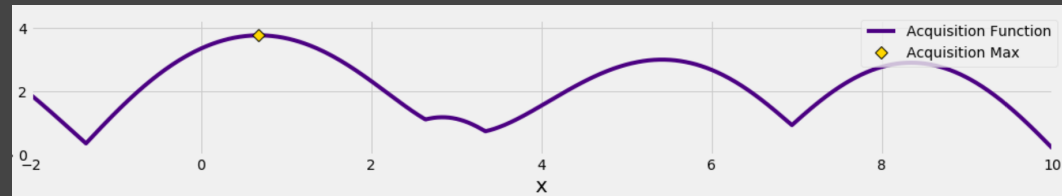
Acquisition
Function



Gaussian Process



CFD



Model Recap

Acquisition
Function



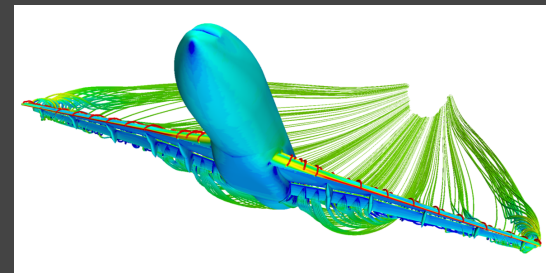
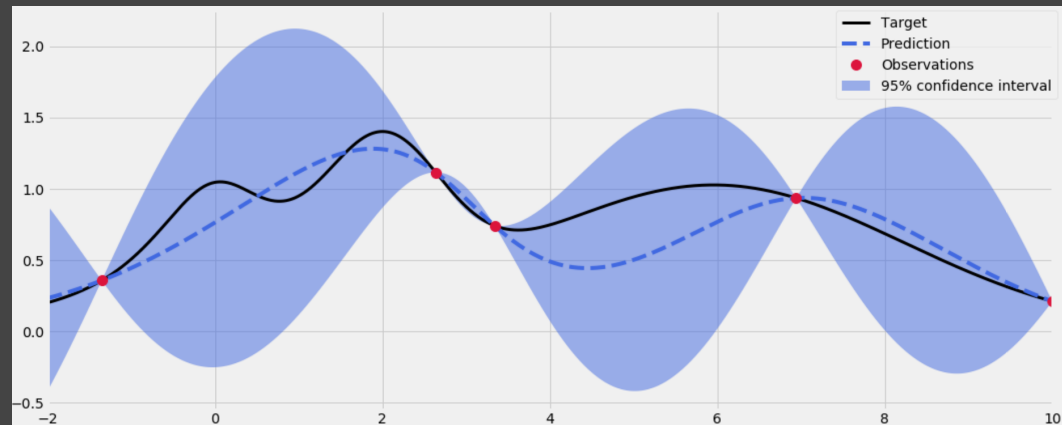
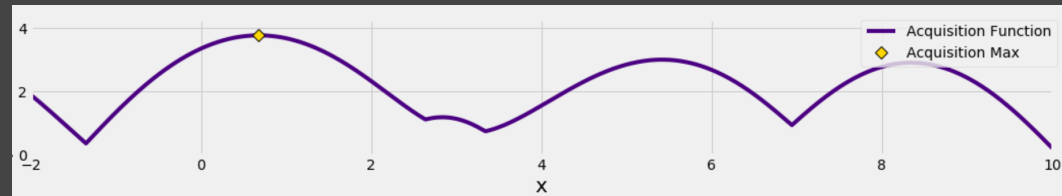
Gaussian Process



CFD



Navier Stokes



$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} + \frac{1}{\rho} \nabla p = \vec{g} + \nu \nabla \cdot \nabla \vec{u}$$

NOPE

$$\nabla \cdot \vec{u} = 0$$

SAIL Algorithm

**Setup: Create Gaussian
Process**

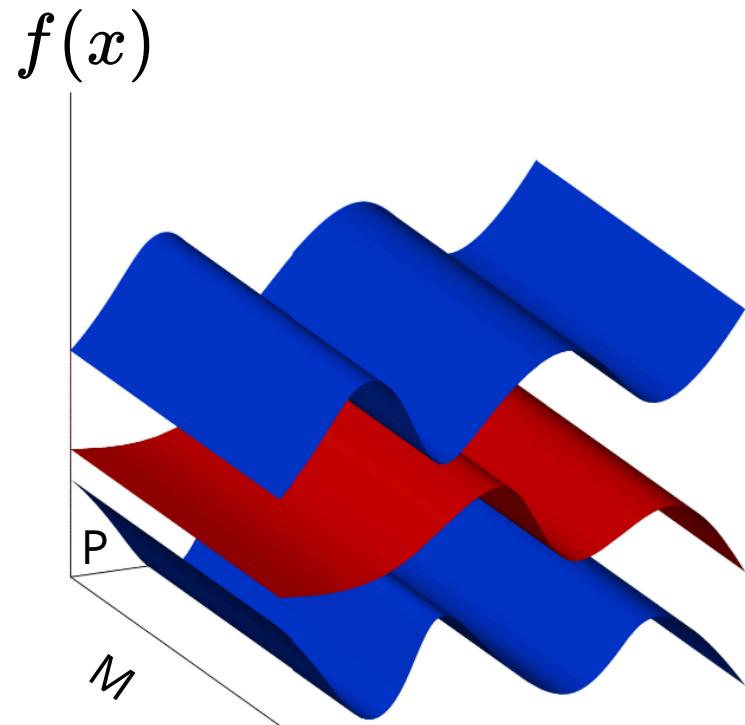
**Evolution: Produce
Acquisition Map**

**Termination: Produce
Prediction Map**

SAIL Algorithm

Setup: Create Gaussian Process

- Select random individuals
- Create Gaussian process



SAIL Algorithm

Evolution: Produce

Acquisition Map

Within computational budget:

- Create acquisition function
- Illuminate with MAP-Elites

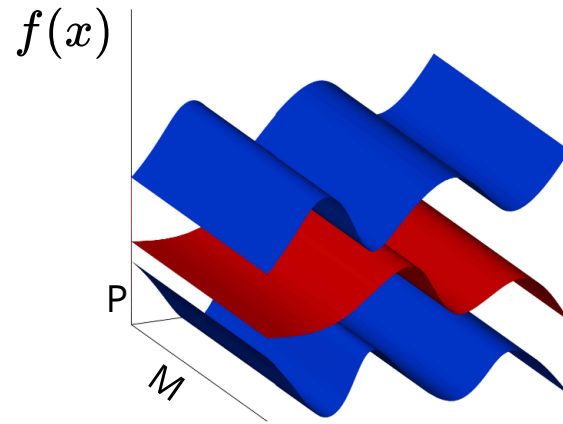
SAIL Algorithm

Evolution: Produce

Acquisition Map

Within computational budget:

- Create acquisition function
- Illuminate with MAP-Elites

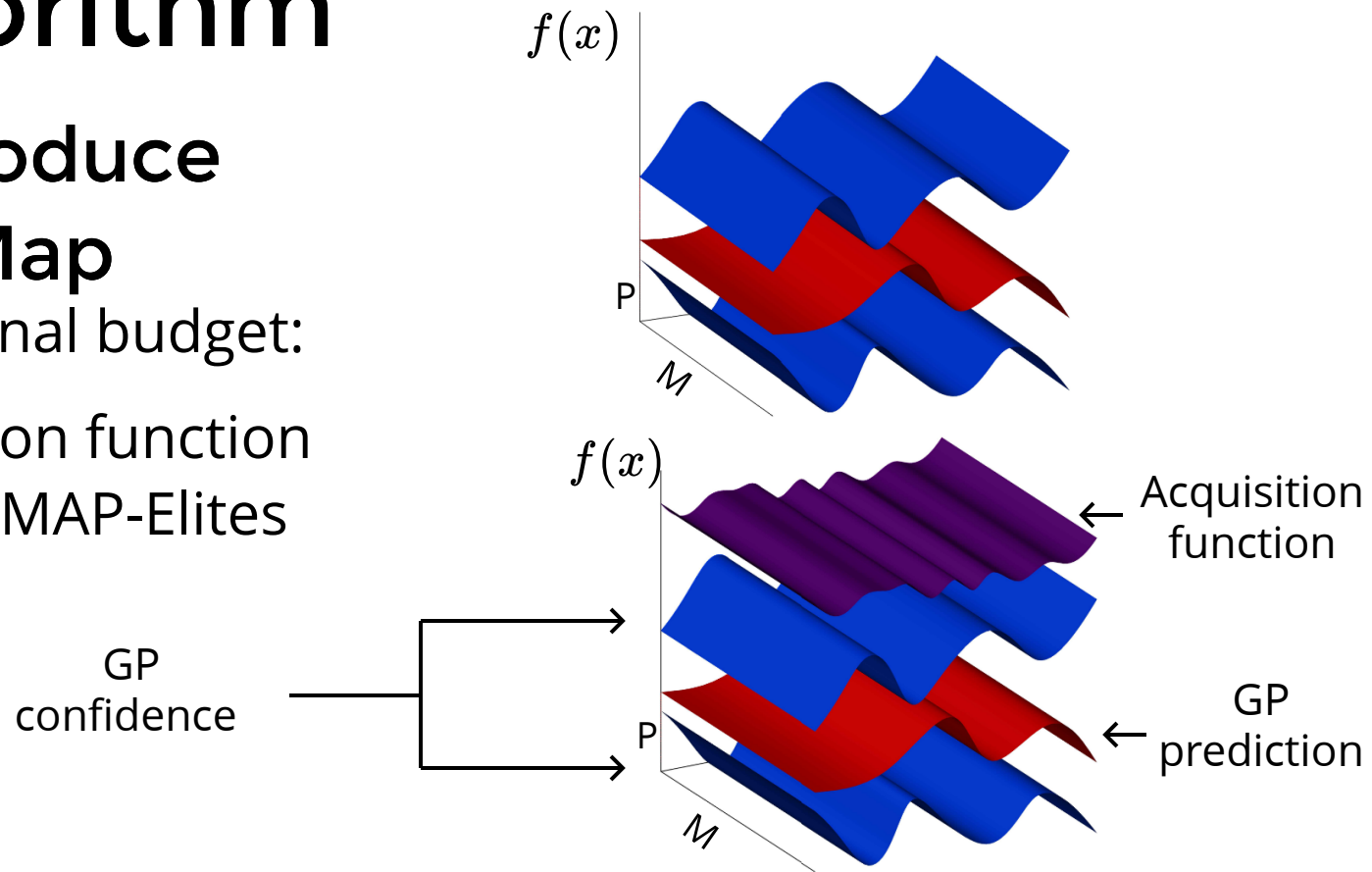


SAIL Algorithm

Evolution: Produce Acquisition Map

Within computational budget:

- Create acquisition function
- Illuminate with MAP-Elites

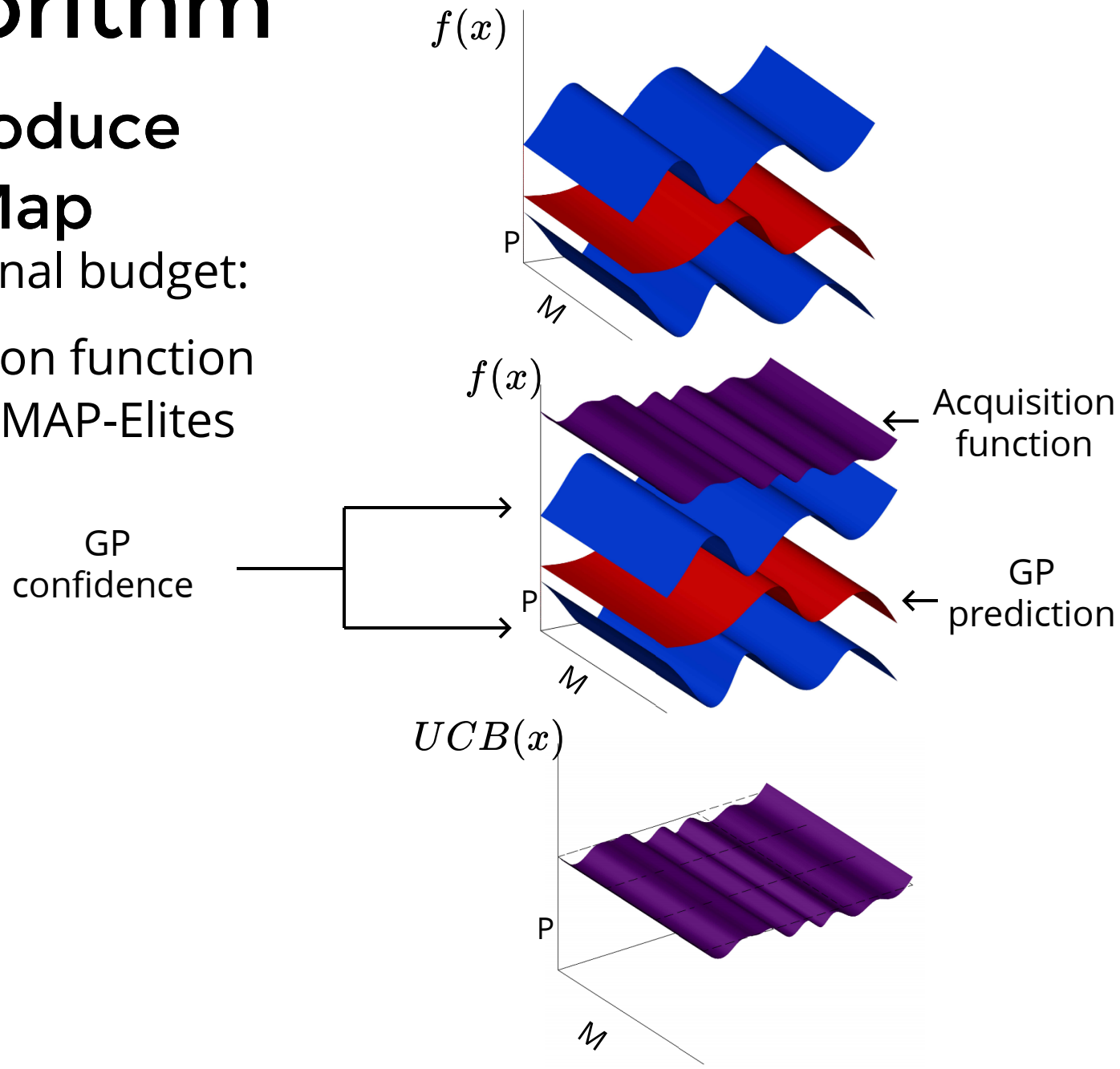


SAIL Algorithm

Evolution: Produce Acquisition Map

Within computational budget:

- Create acquisition function
- Illuminate with MAP-Elites



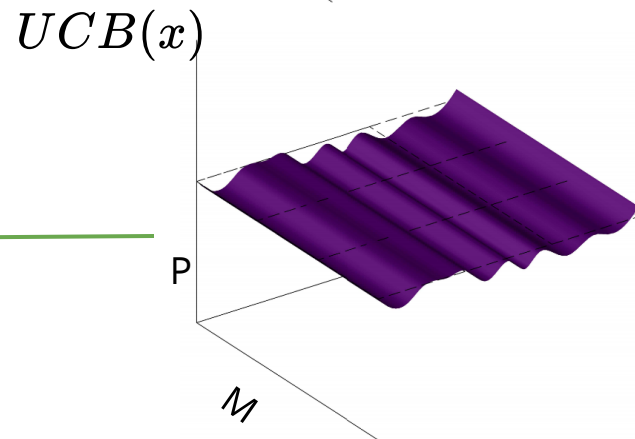
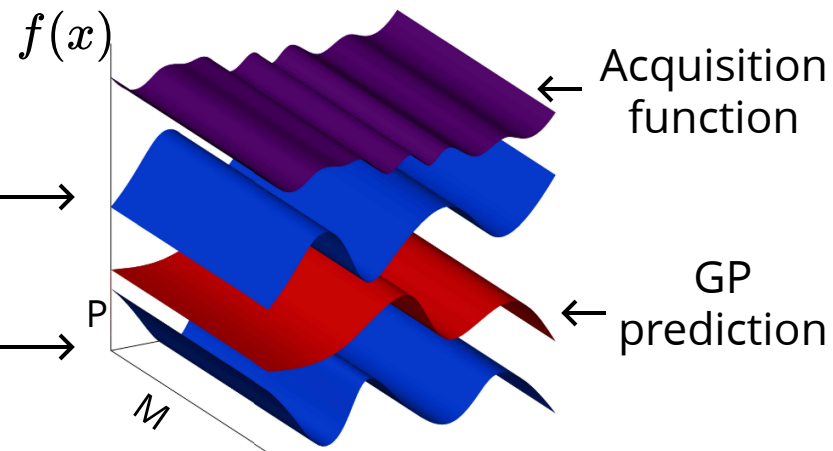
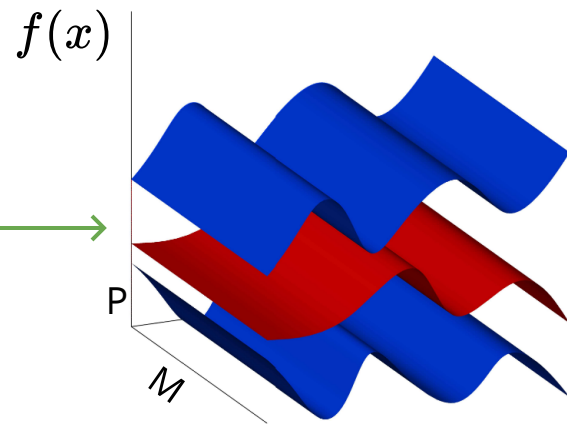
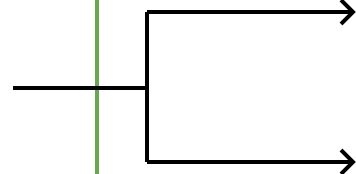
SAIL Algorithm

Evolution: Produce Acquisition Map

Within computational budget:

- Create acquisition function
- Illuminate with MAP-Elites

GP confidence



SAIL Algorithm

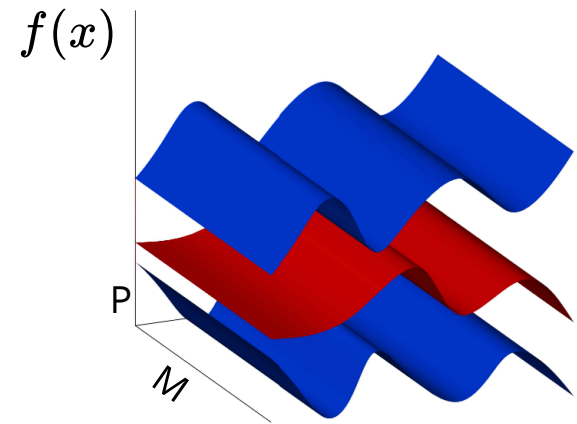
Termination: Produce Prediction Map

- Grab only the GP-Prediction
- Illuminate with MAP Elites

SAIL Algorithm

Termination: Produce Prediction Map

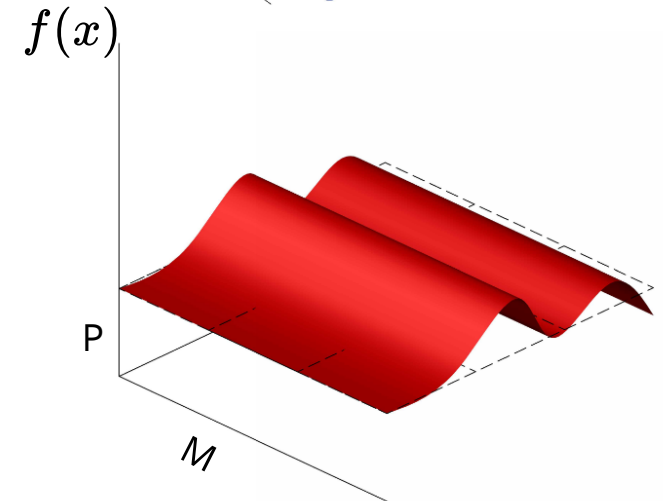
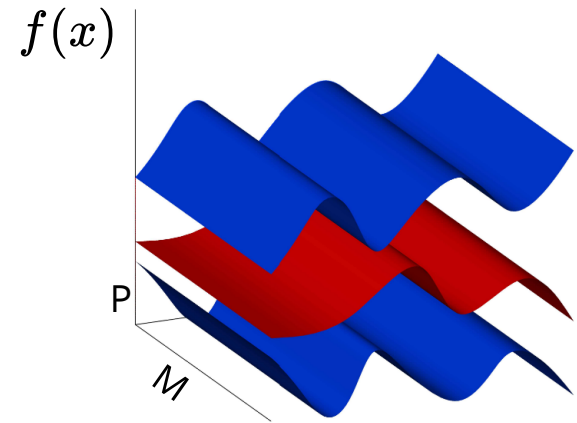
- Grab only the GP-Prediction
- Illuminate with MAP Elites



SAIL Algorithm

Termination: Produce Prediction Map

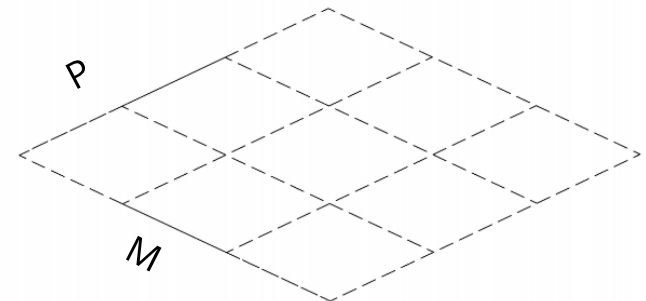
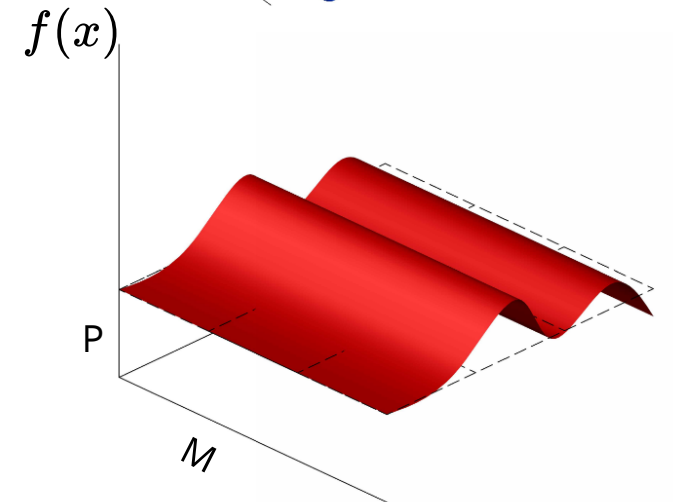
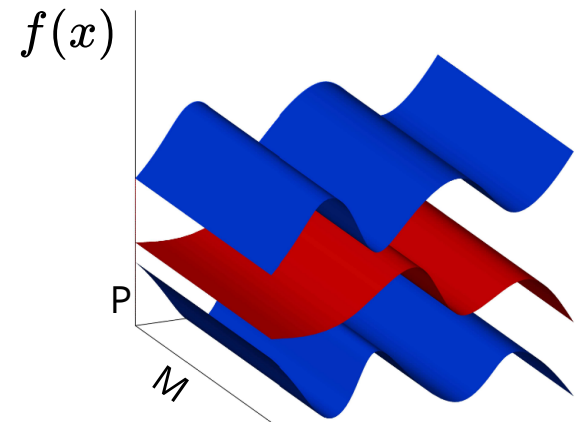
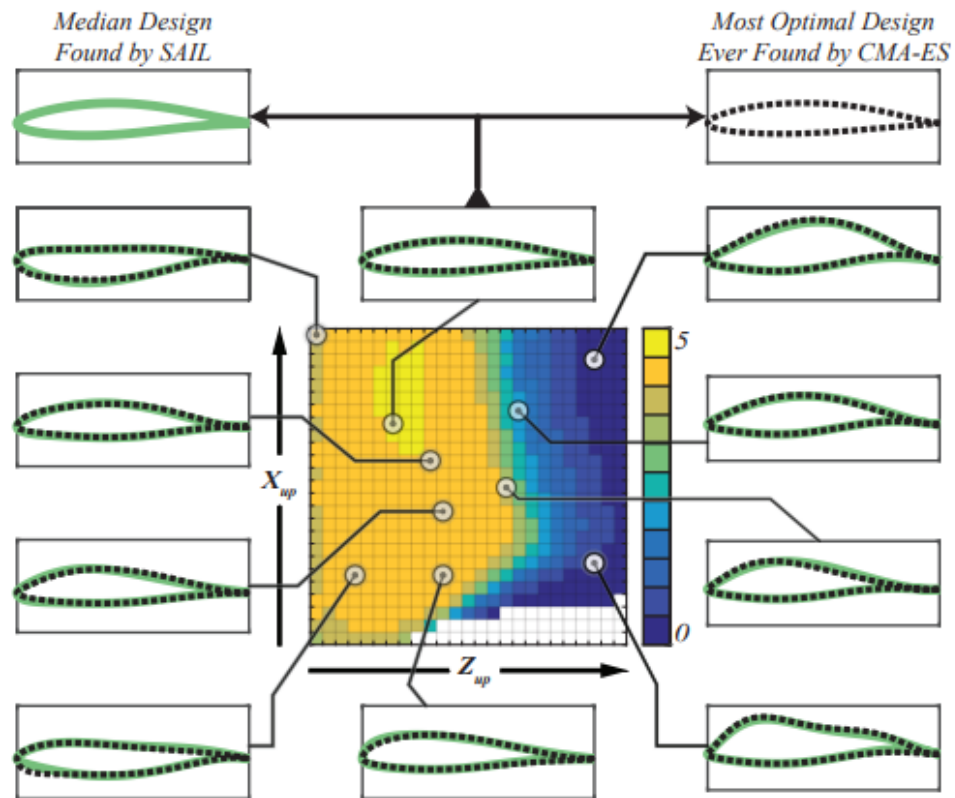
- Grab only the GP-Prediction
- Illuminate with MAP Elites



SAIL Algorithm

Termination: Produce Prediction Map

- Grab only the GP-Prediction
- Illuminate with MAP Elites



Velomobile Experiment



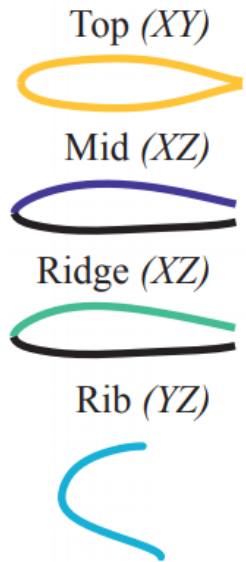
Taken from [1]

Challenges

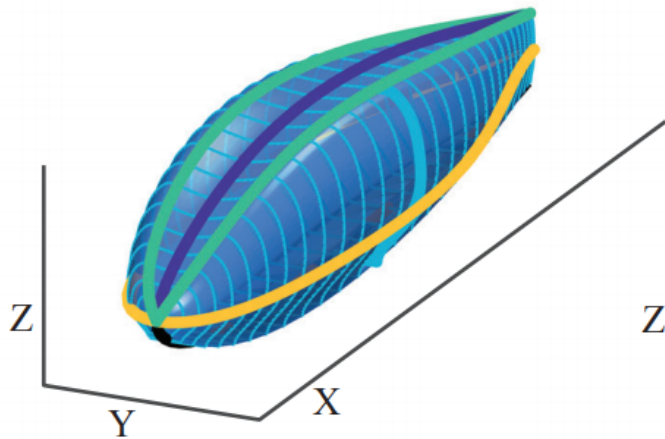
- CFD Simulations for drag calculation are expensive
- How do you represent a velomobile shape?
- How do you run a traditional optimizer here?

Velomobile Experiment Representations

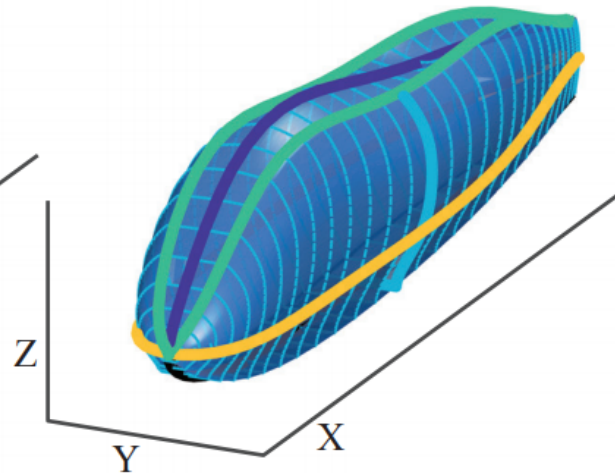
Parameterization



Middle Parameter Values



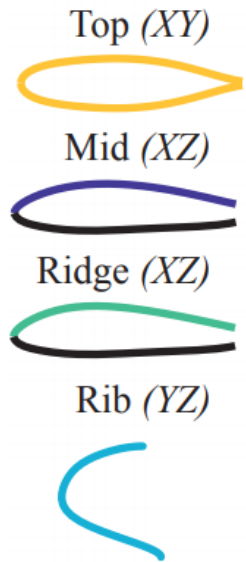
Random Parameter Values



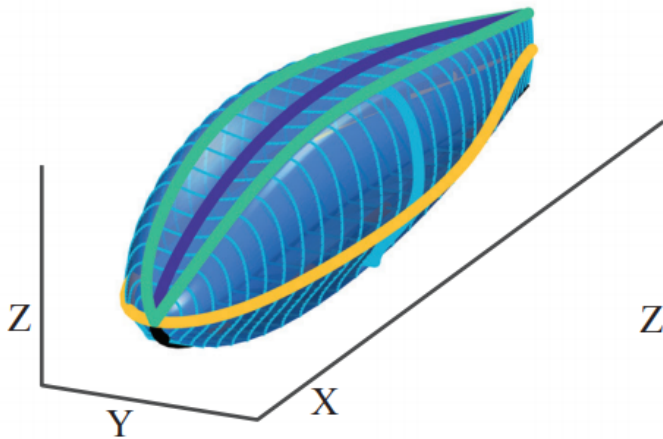
Taken from [1]

Velomobile Experiment Representations

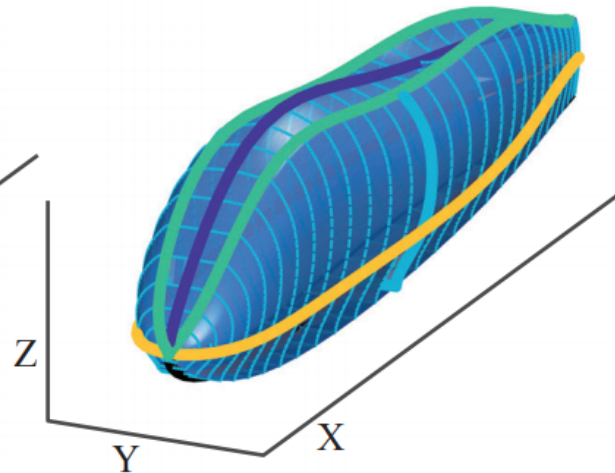
Parameterization



Middle Parameter Values



Random Parameter Values



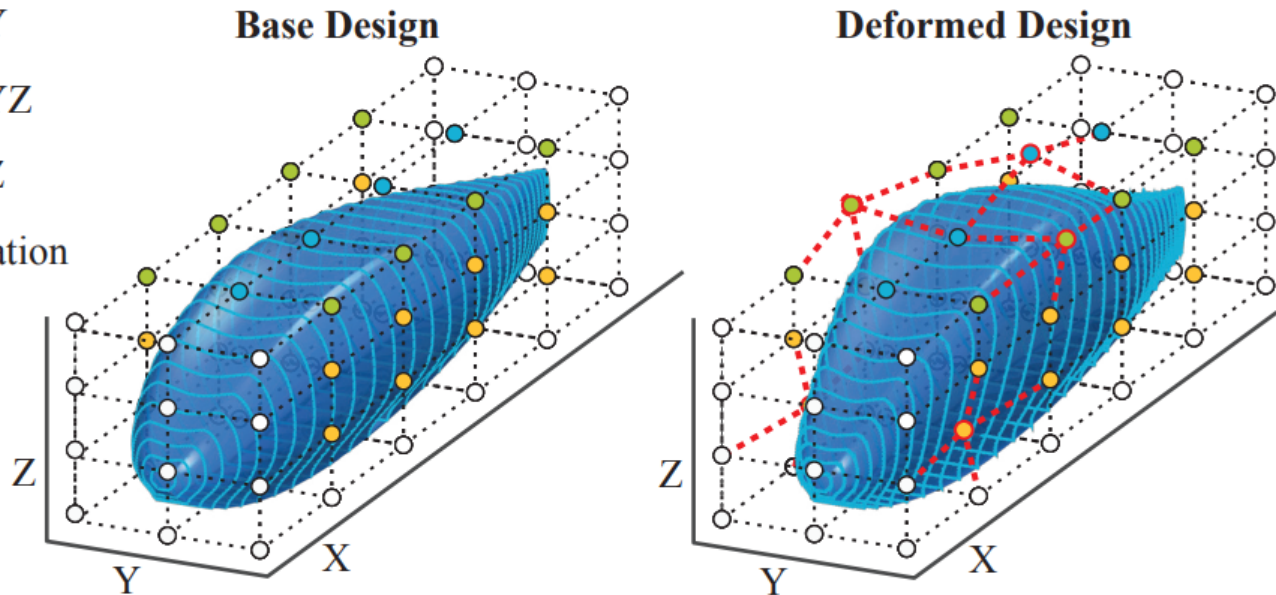
Taken from [1]

16 parameters

Velomobile Experiment Representations

Deformation

- Deform in Y
- Deform in YZ
- Deform in Z
- No Deformation

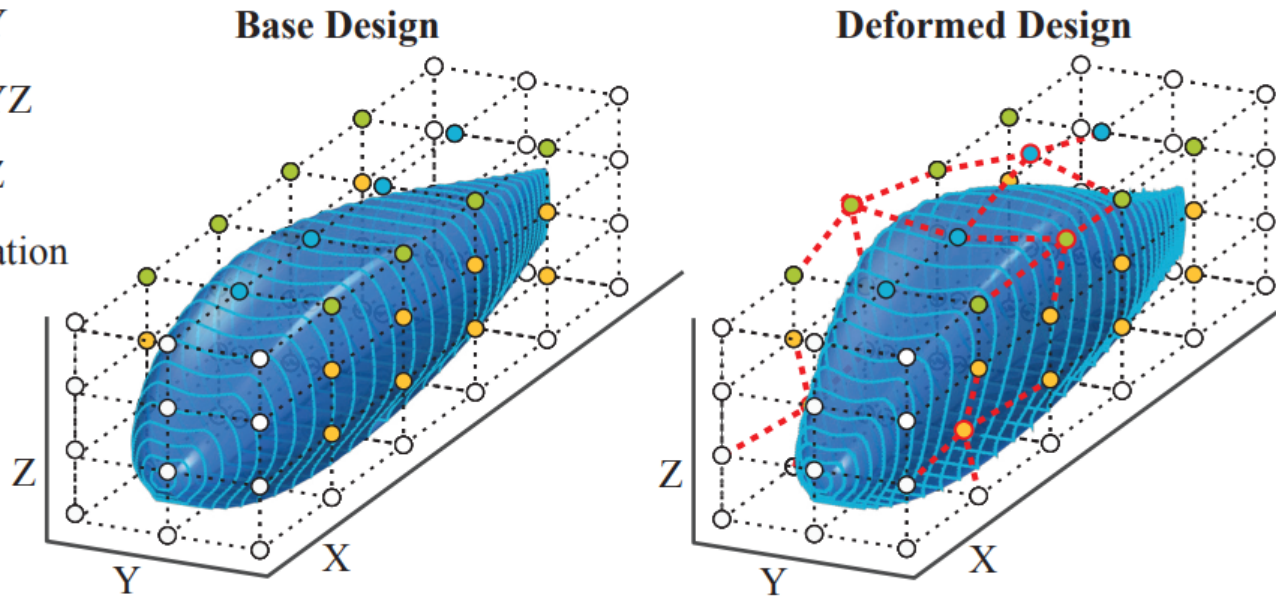


Taken from [1]

Velomobile Experiment Representations

Deformation

- Deform in Y
- Deform in YZ
- Deform in Z
- No Deformation

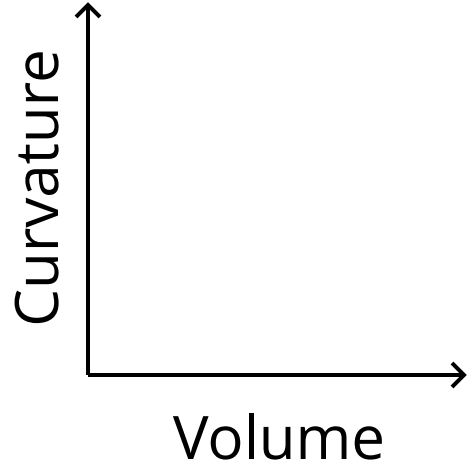


16 parameters

Taken from [1]

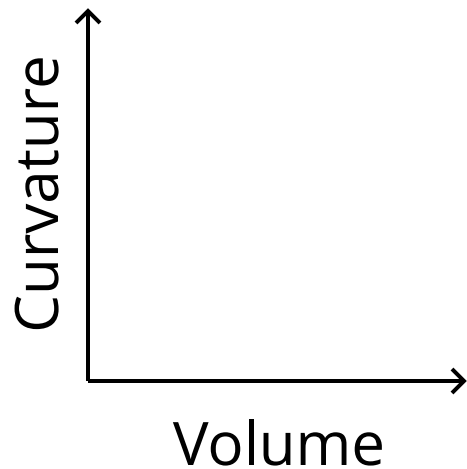
Velomobile Experiment Setup

Velomobile Experiment Setup



**Feature
Space**

Velomobile Experiment Setup



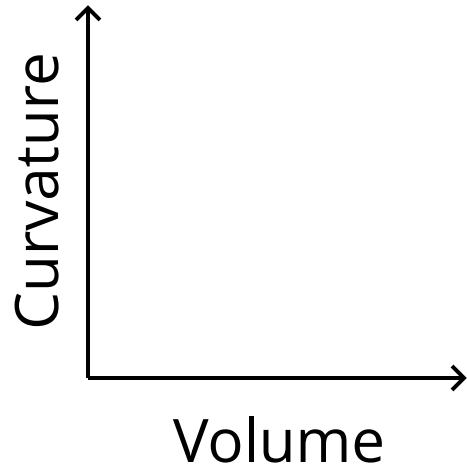
**Feature
Space**



Drag

**Fitness
Function**

Velomobile Experiment Setup



**Feature
Space**

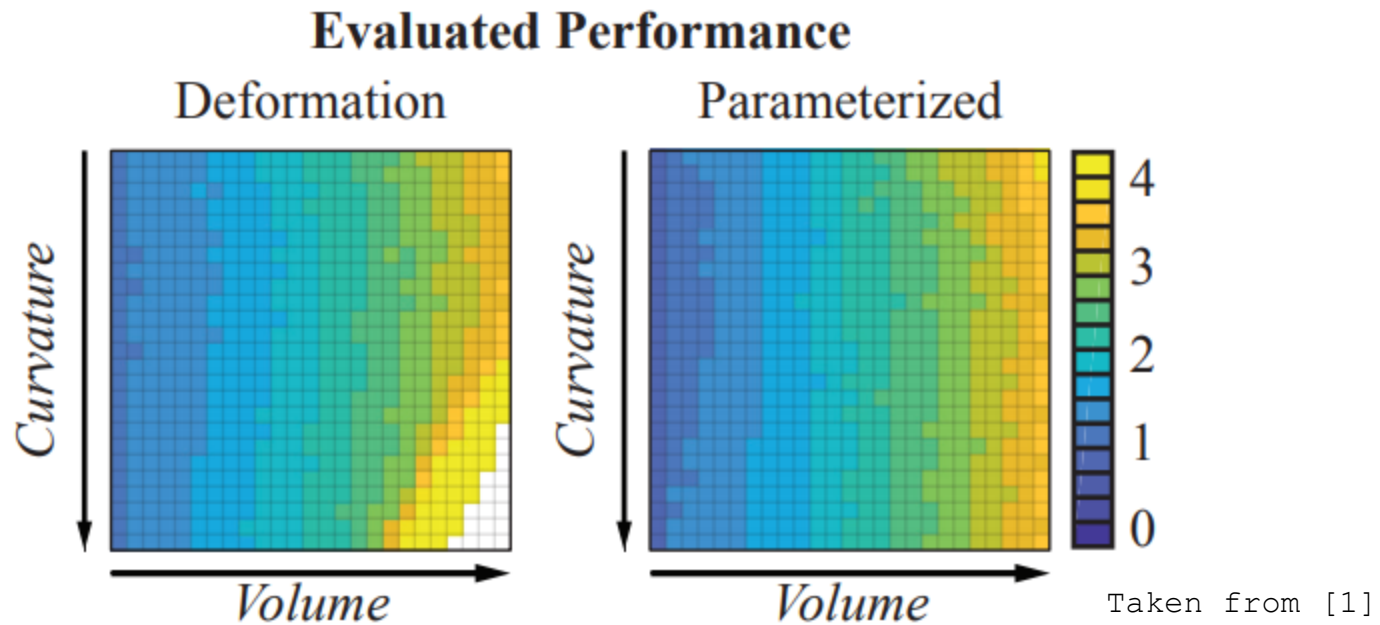


Drag

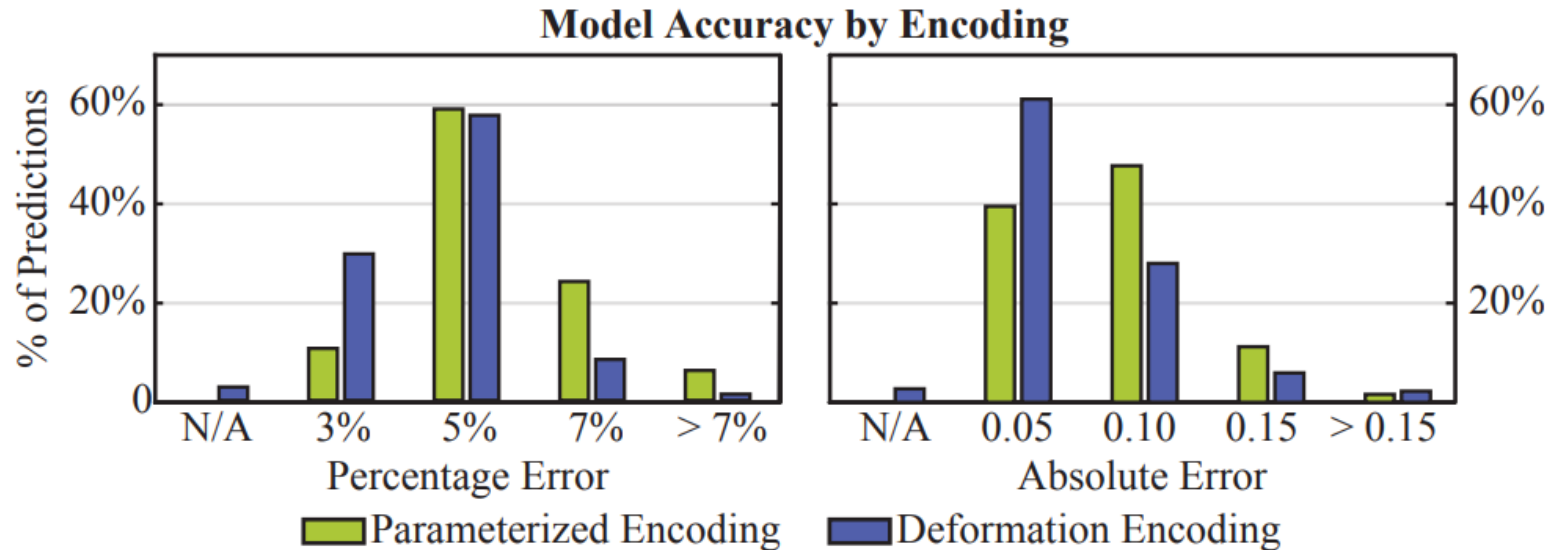
**Fitness
Function**

No optimizer or MAP-Elites

Velomobile Experiment Results

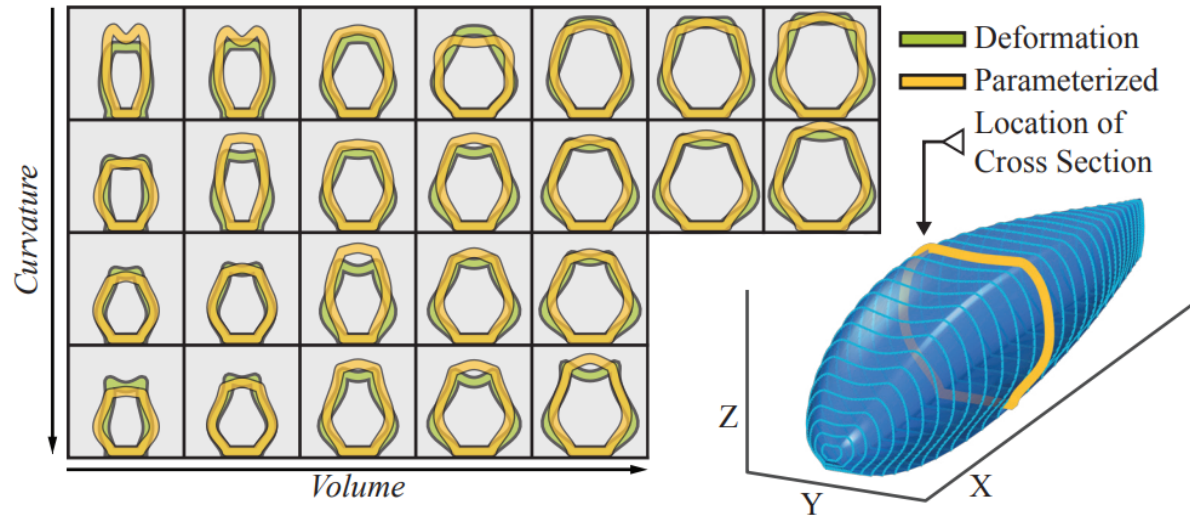


Velomobile Experiment Results



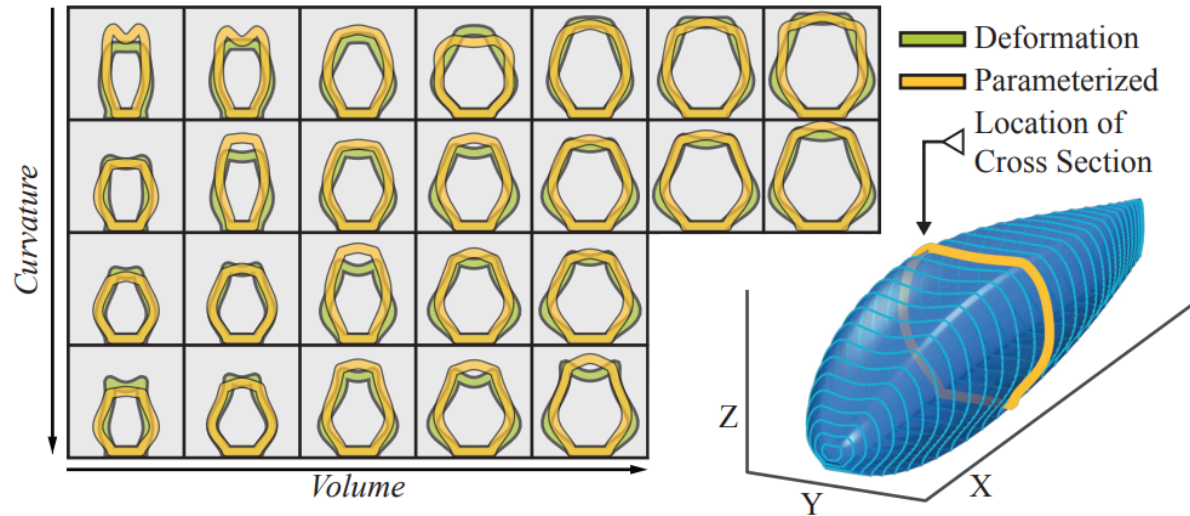
Taken from [1]

Velomobile Experiment Results



Taken from [1]

Velomobile Experiment Results



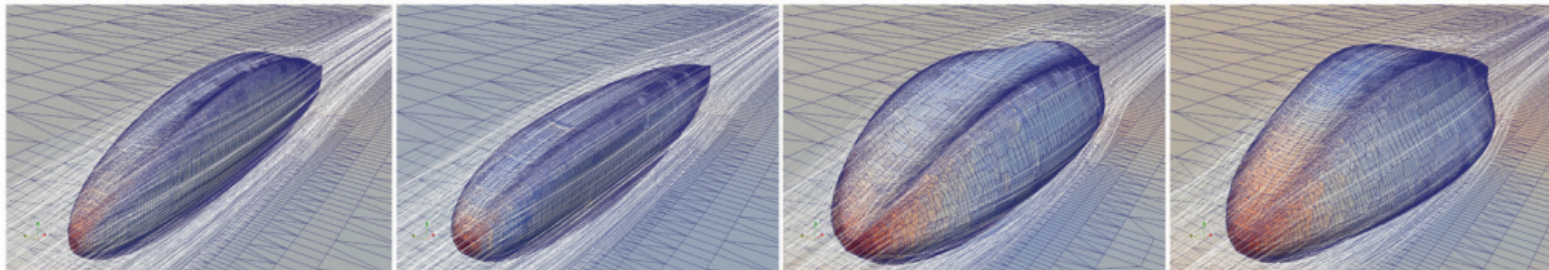
Taken from [1]

Parameterized
1.19 N

Deformation
1.44 N

Parameterized
3.56 N

Deformation
3.12 N



Acknowledgments

Acknowledgments

- Andrew Kroska and Shawn Saliyev

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Citations

[1] Adam Gaier, Alexander Asteroth, Jean-Baptiste Mouret.
Data-Efficient Design Exploration through Surrogate-Assisted
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Citations

[1] Adam Gaier, Alexander Asteroth, Jean-Baptiste Mouret.
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Questions?

Get in touch!

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