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Compressed Optimization of Device Architectures (CODA) for Semiconductor Quantum Devices

Adam Frees

John King Gamble, Daniel R. Ward, Robin Blume-Kohout, M. A. Eriksson, Mark Friesen, and S. N. Coppersmith

March 6, 2018

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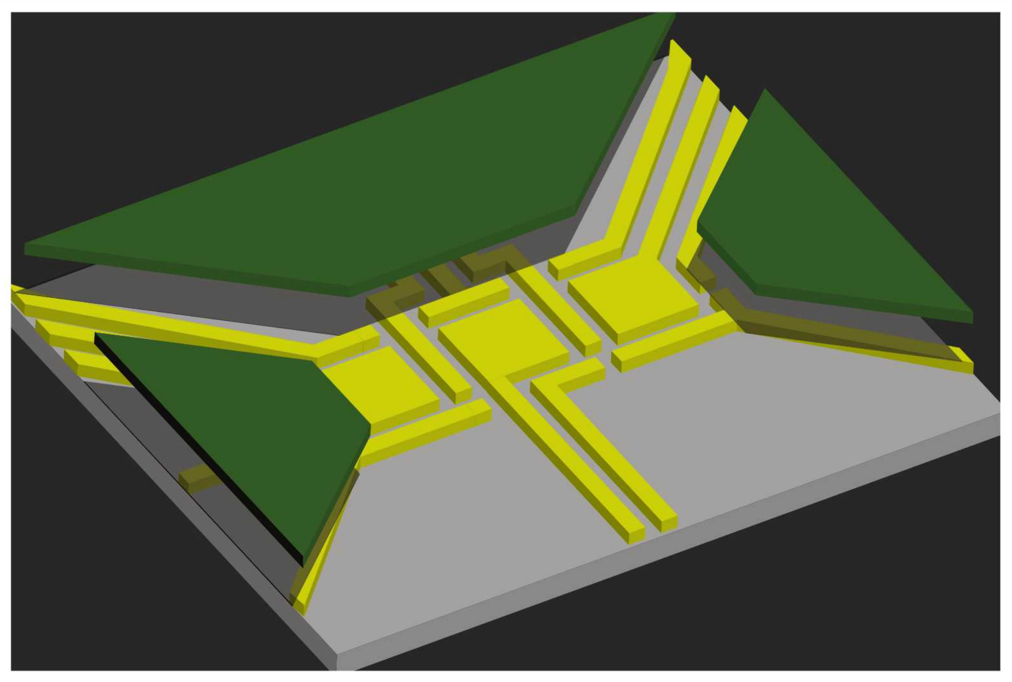
The goal: to develop a robust tool and scalable tool for optimizing the tuning and design of semiconductor devices

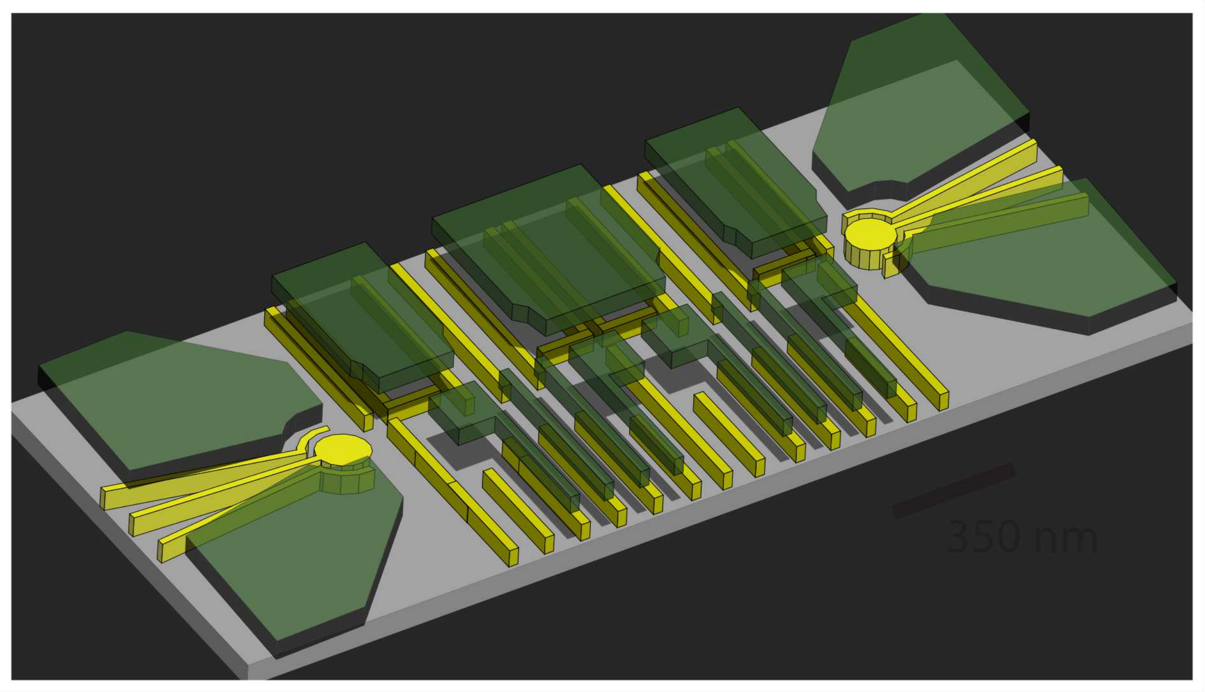
- As semiconductor-based quantum devices become larger and more complex, computer-aided design becomes a necessity

- In particular, designing devices which are easily "tunable" can become challenging

  - "Tunable" - able to independently control a quantity of interest (e.g. tunnel coupling) by changing voltages on a small number of electrodes

- The CODA procedure can automatically and objectively compare the "tunability" of different device designs





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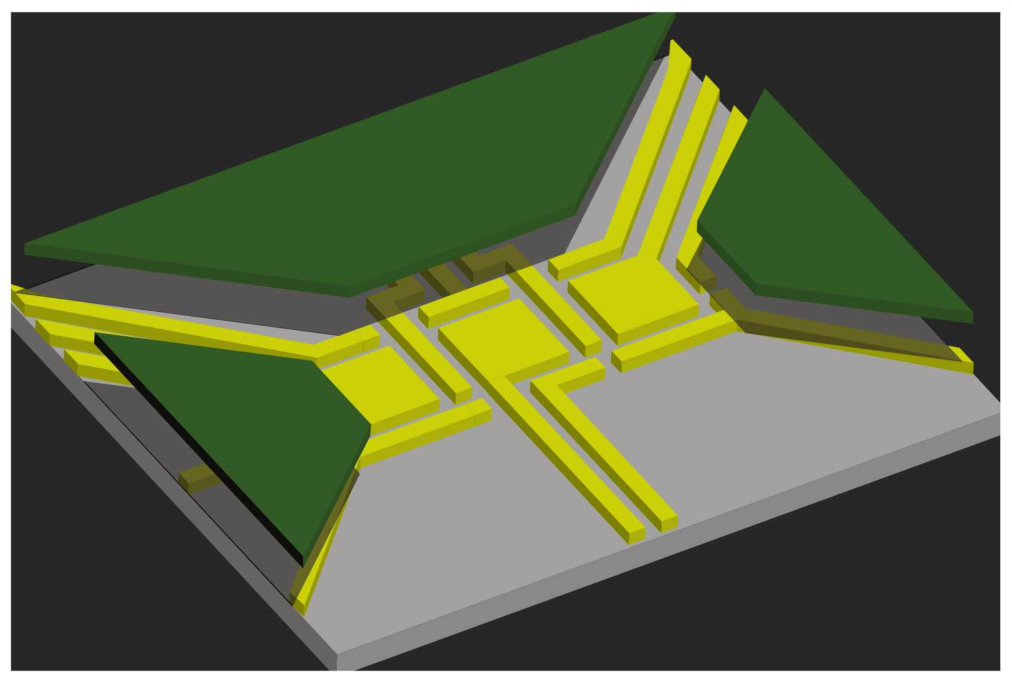

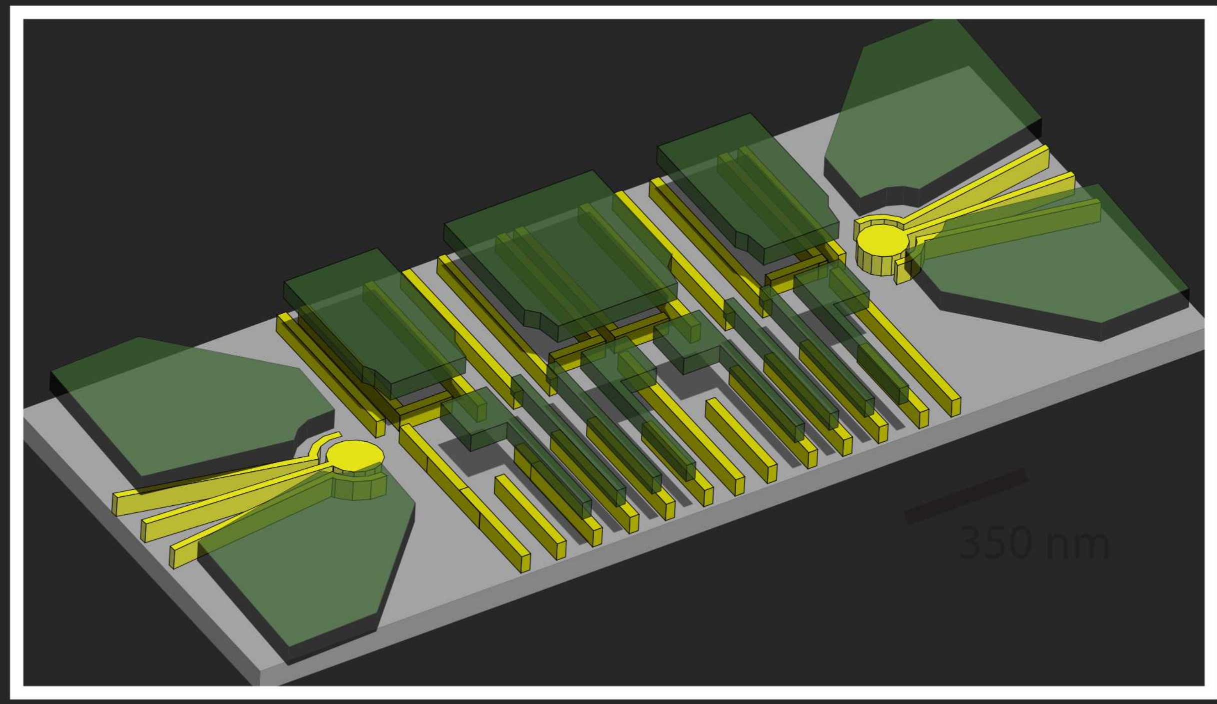

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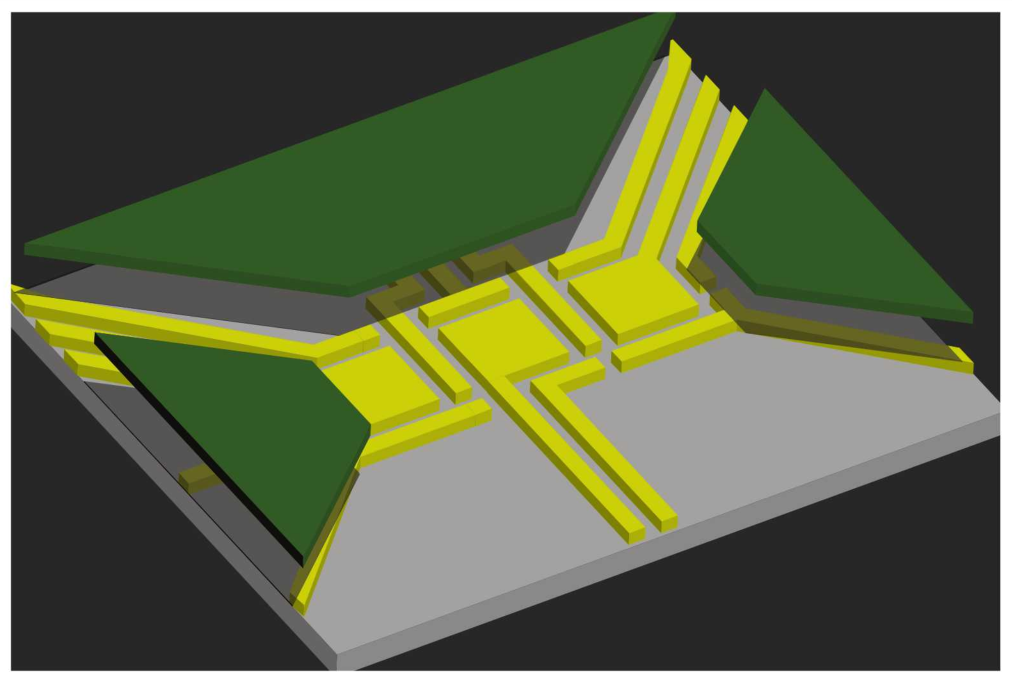

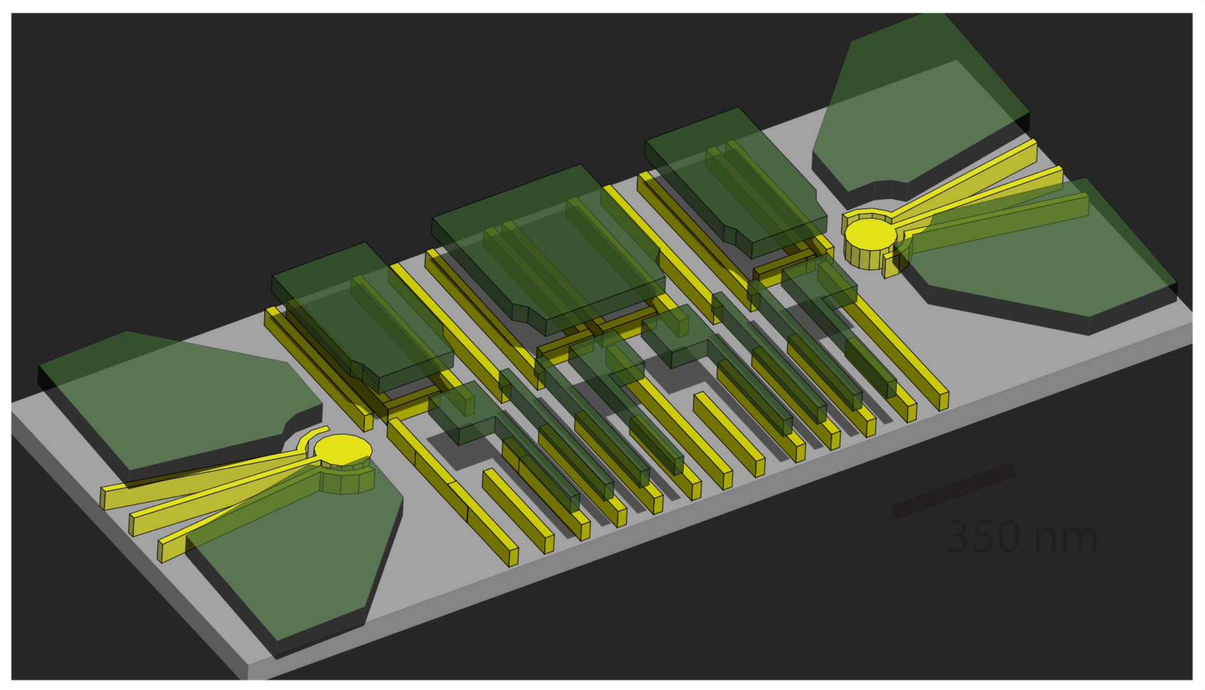

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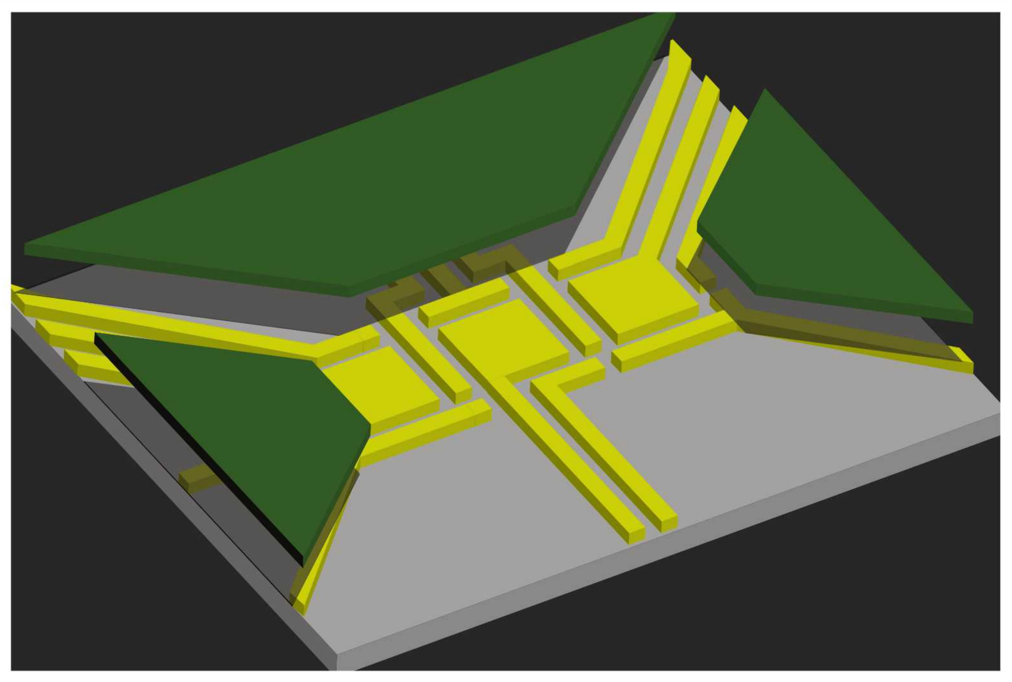

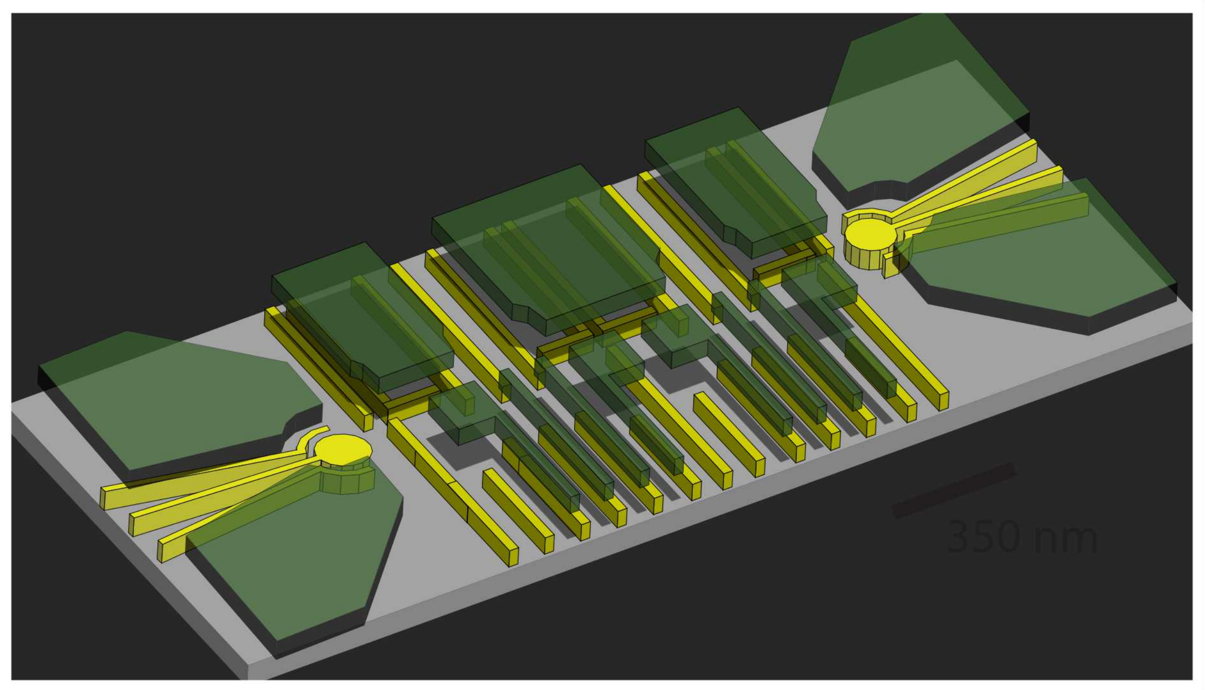

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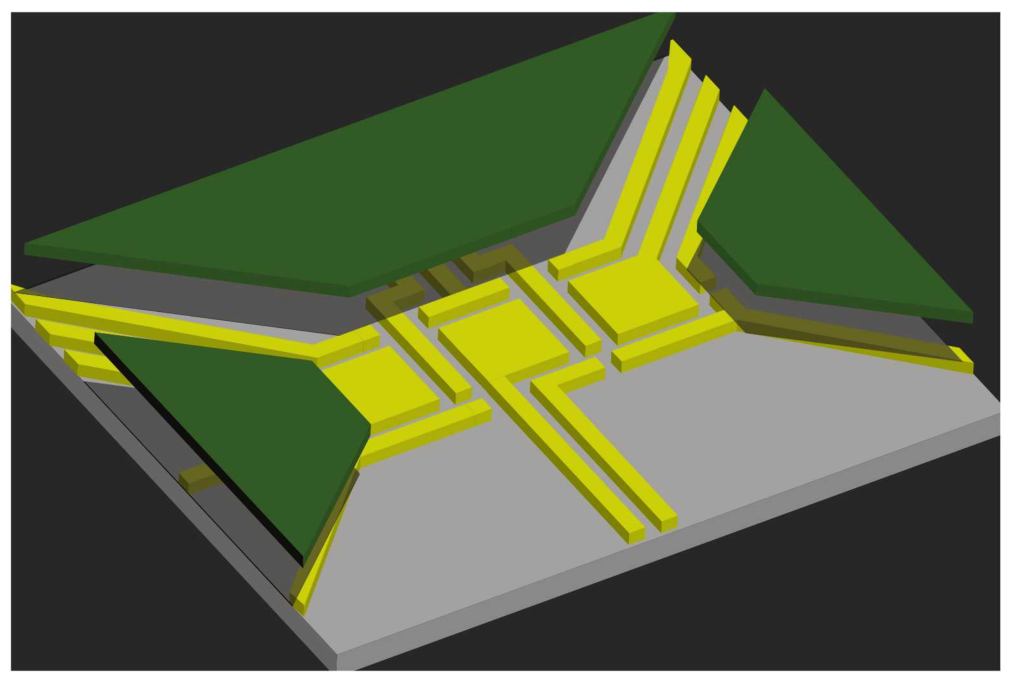

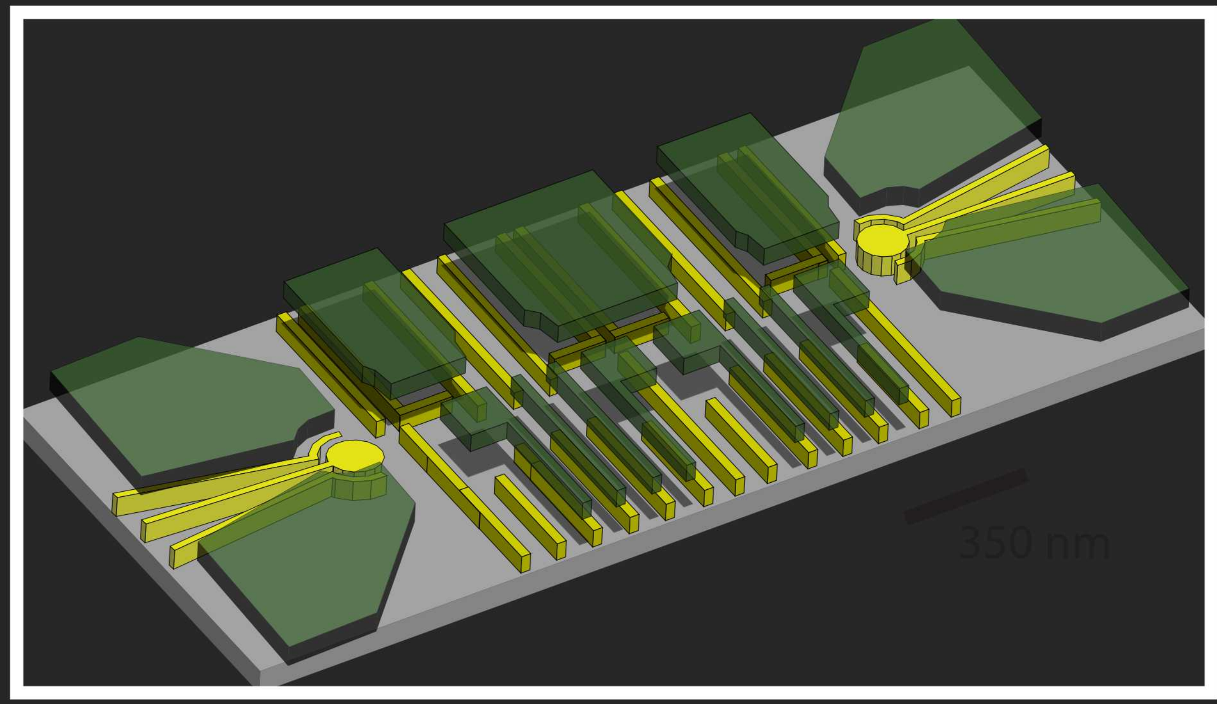

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Naive gradient descent can be used to tune a device, but will not necessarily yield the easiest way to tune the device

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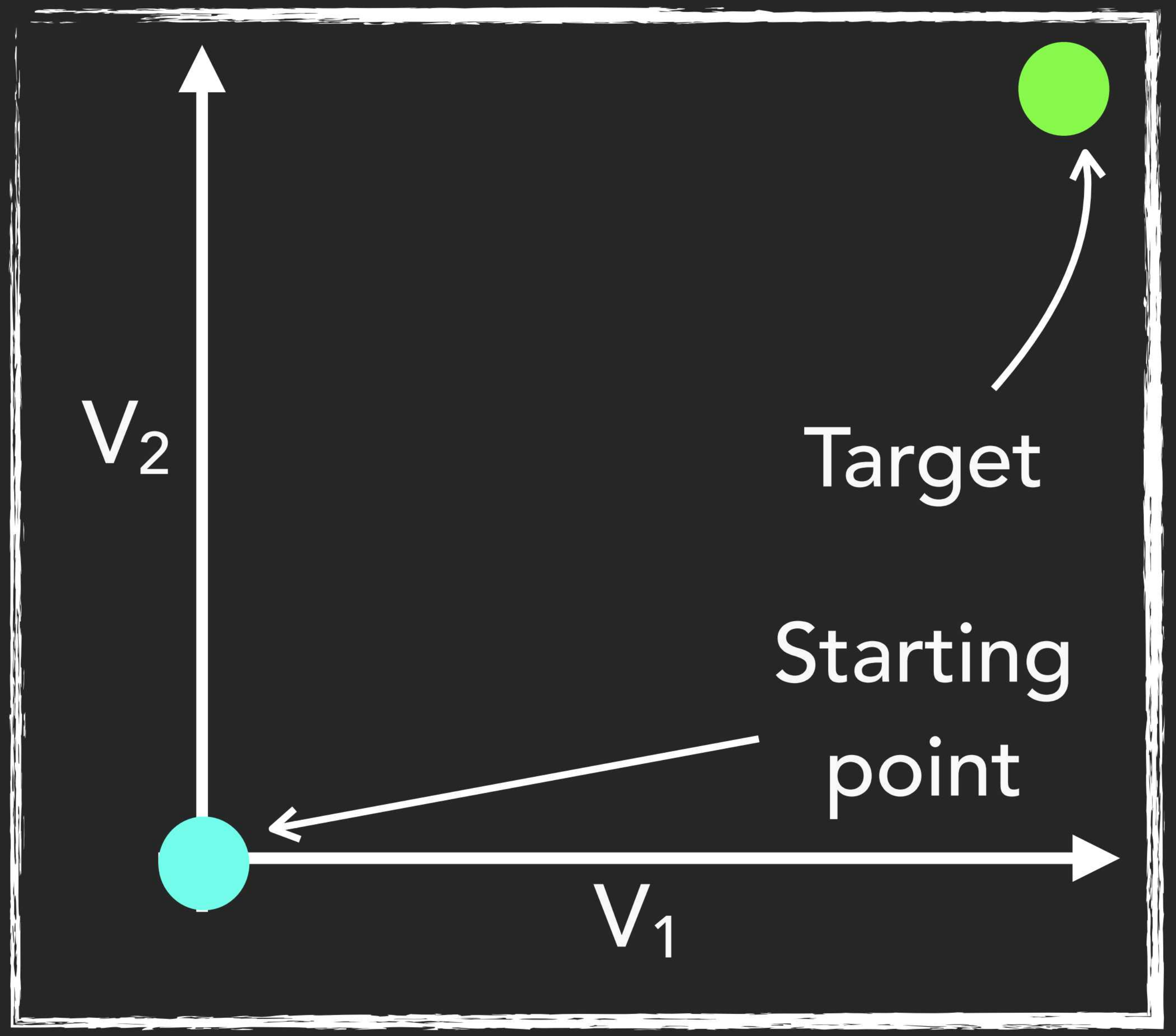

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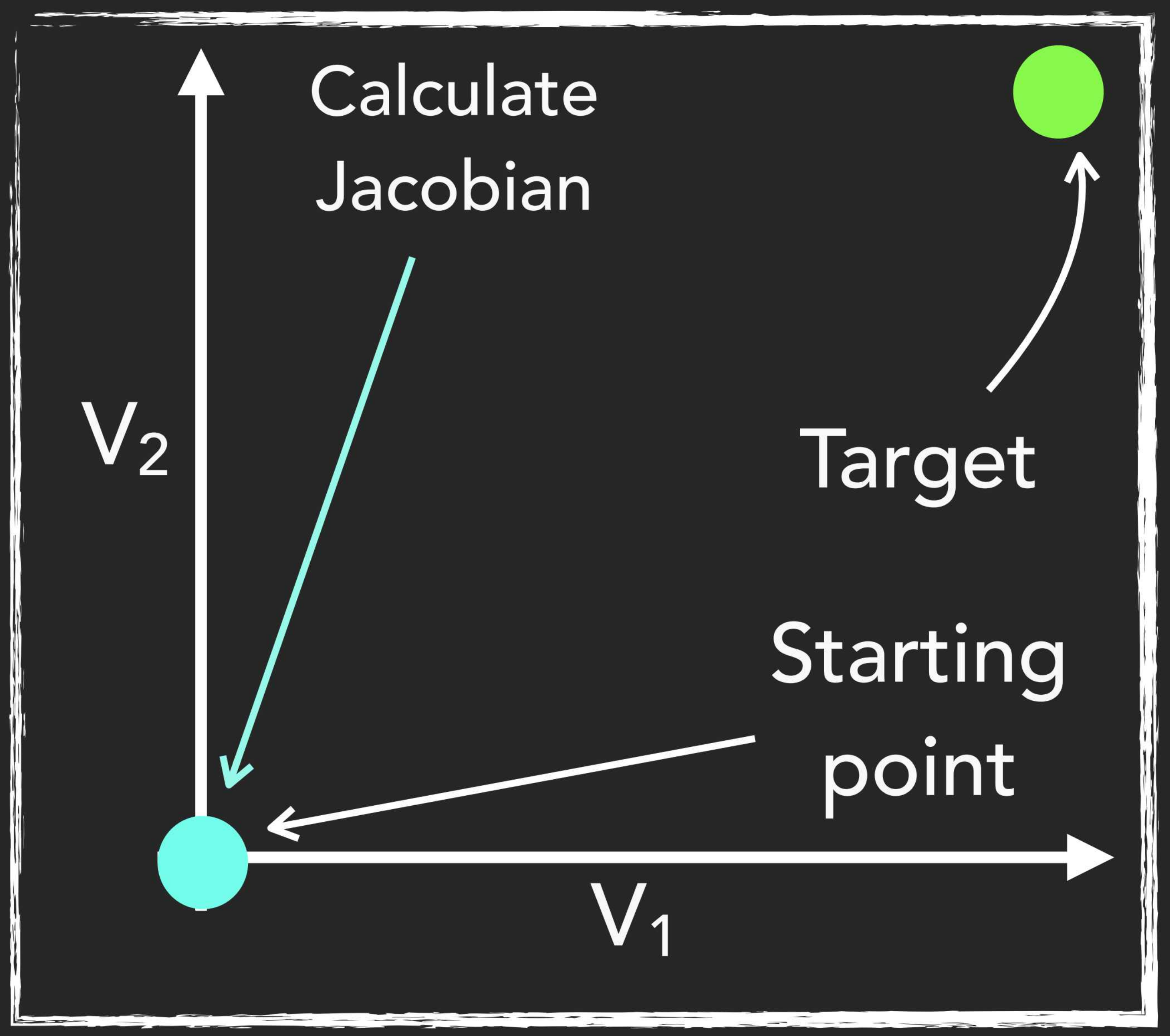
List of voltage changes on electrodes

Desired change in quantities of interest



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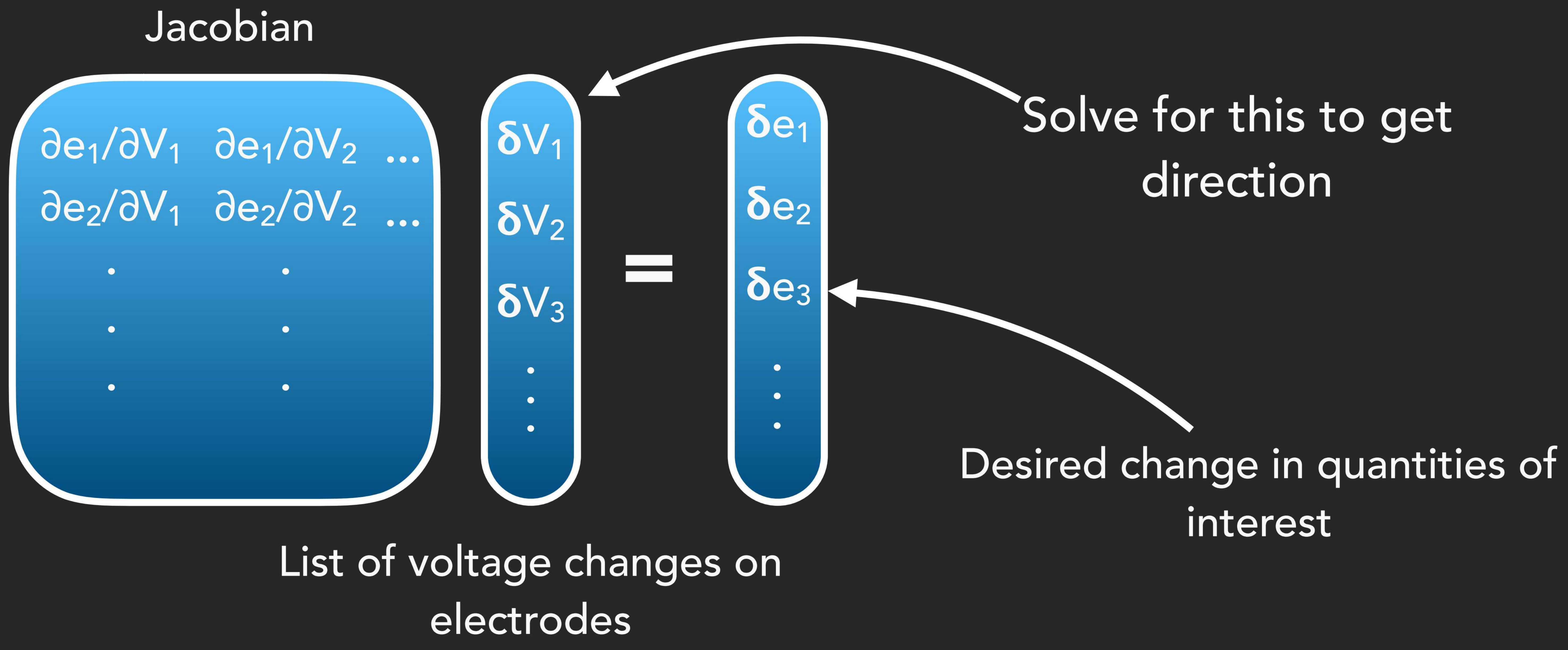

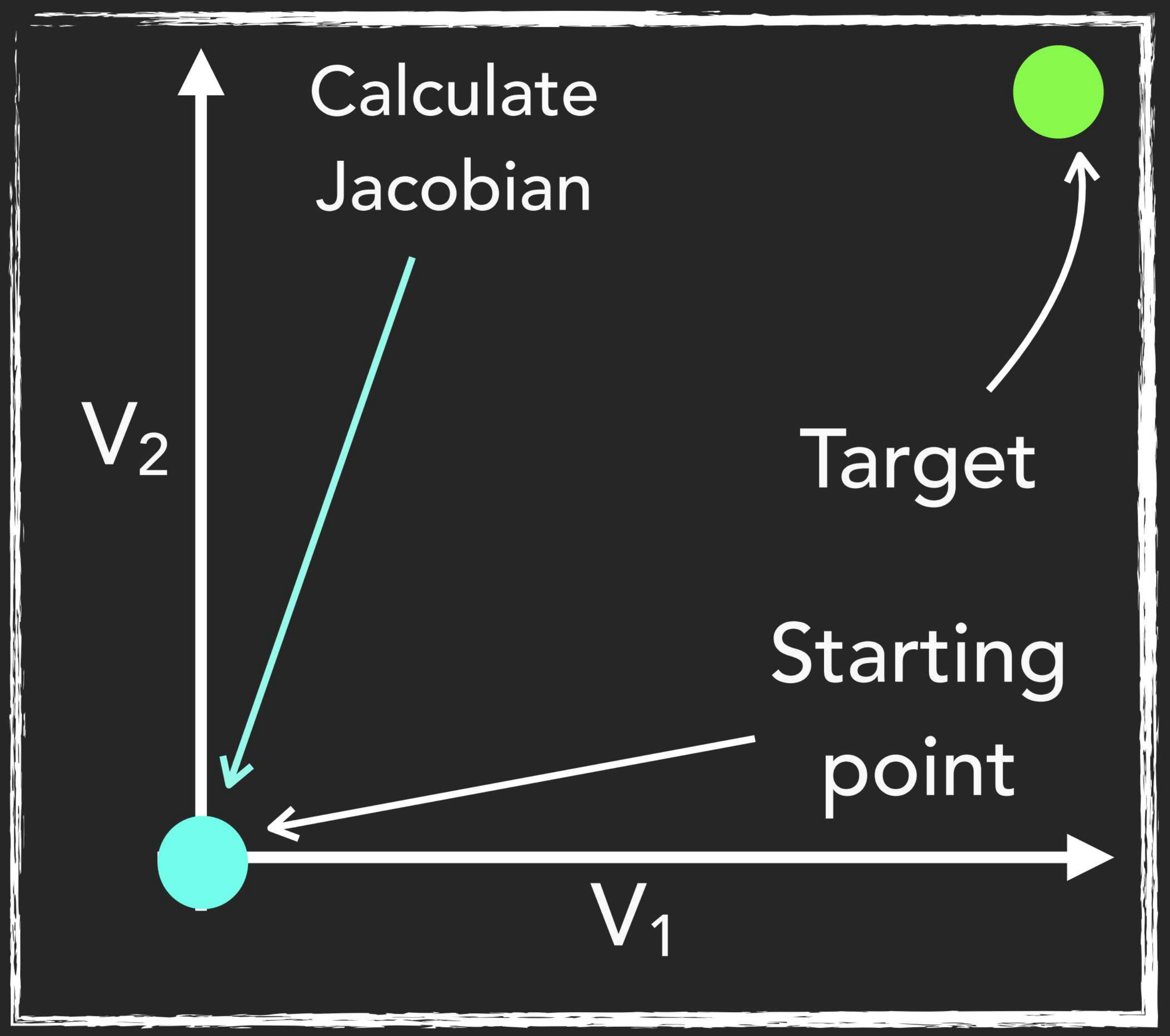

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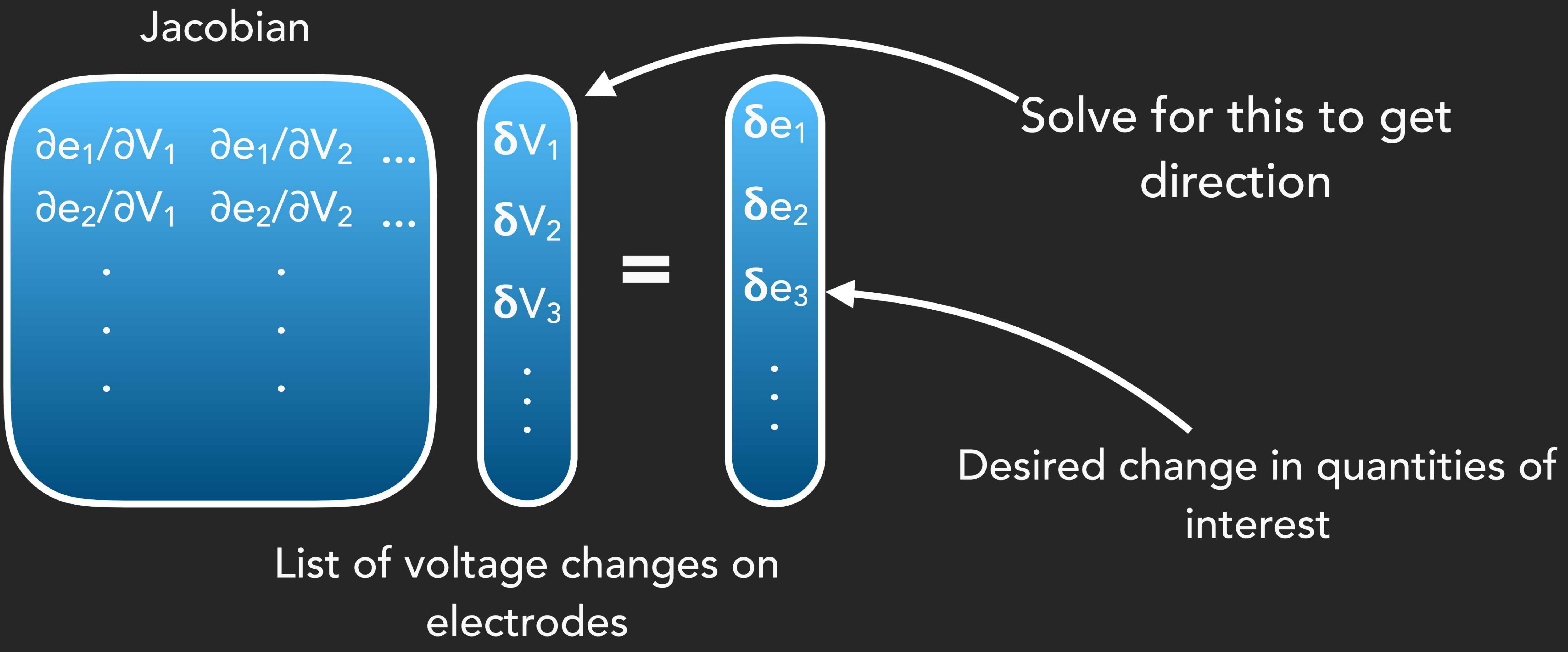

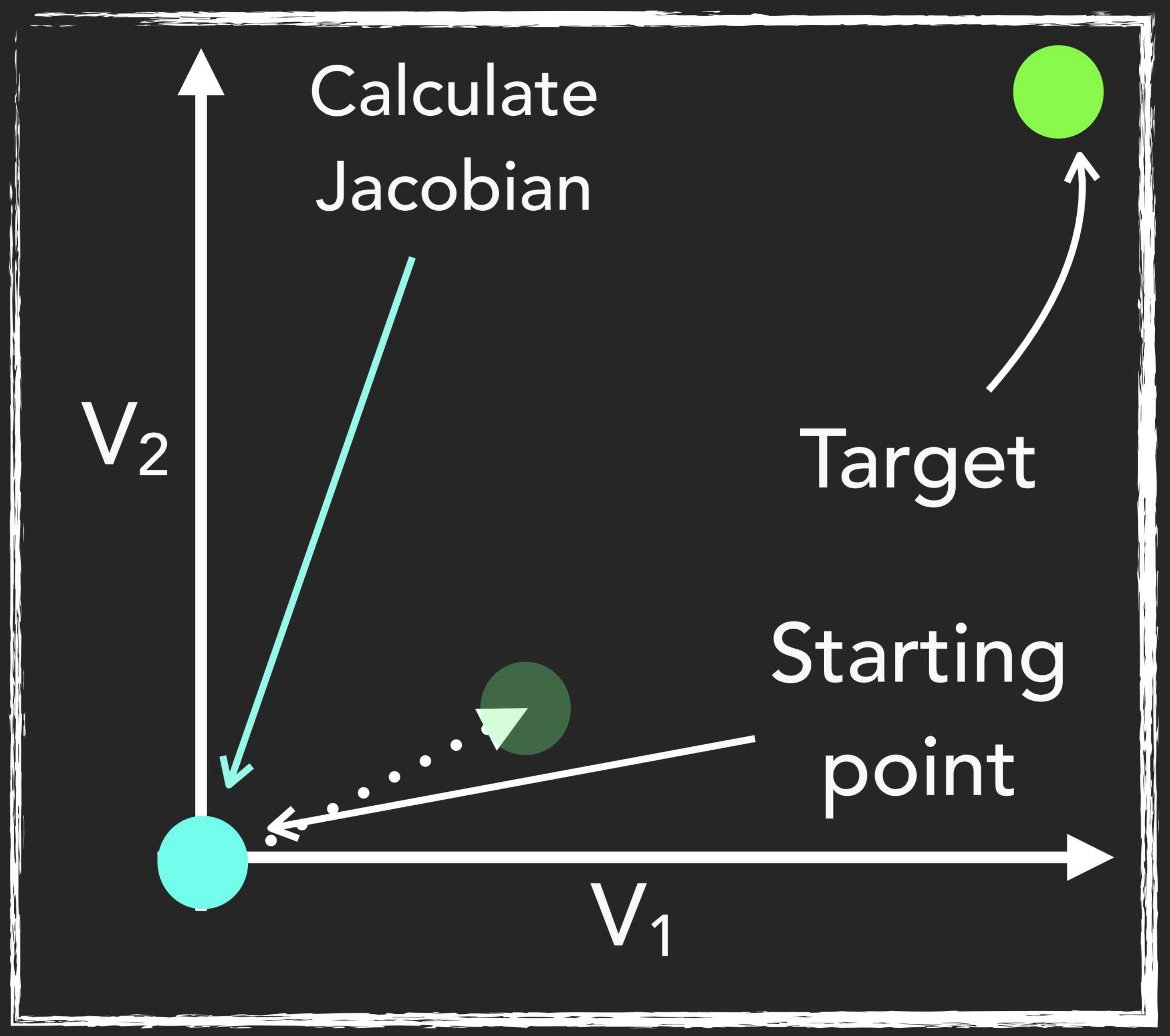

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Solve for this to get direction

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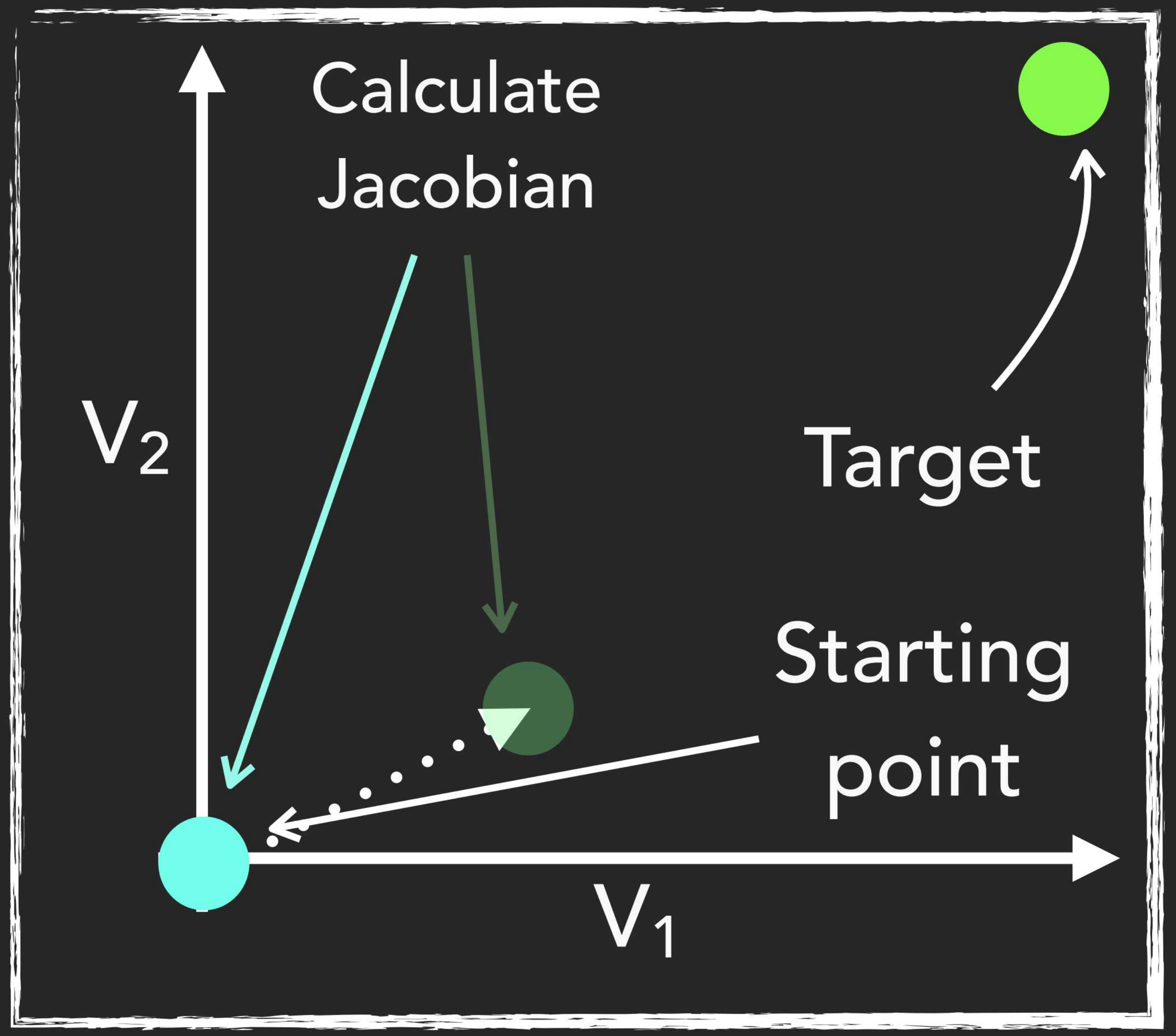

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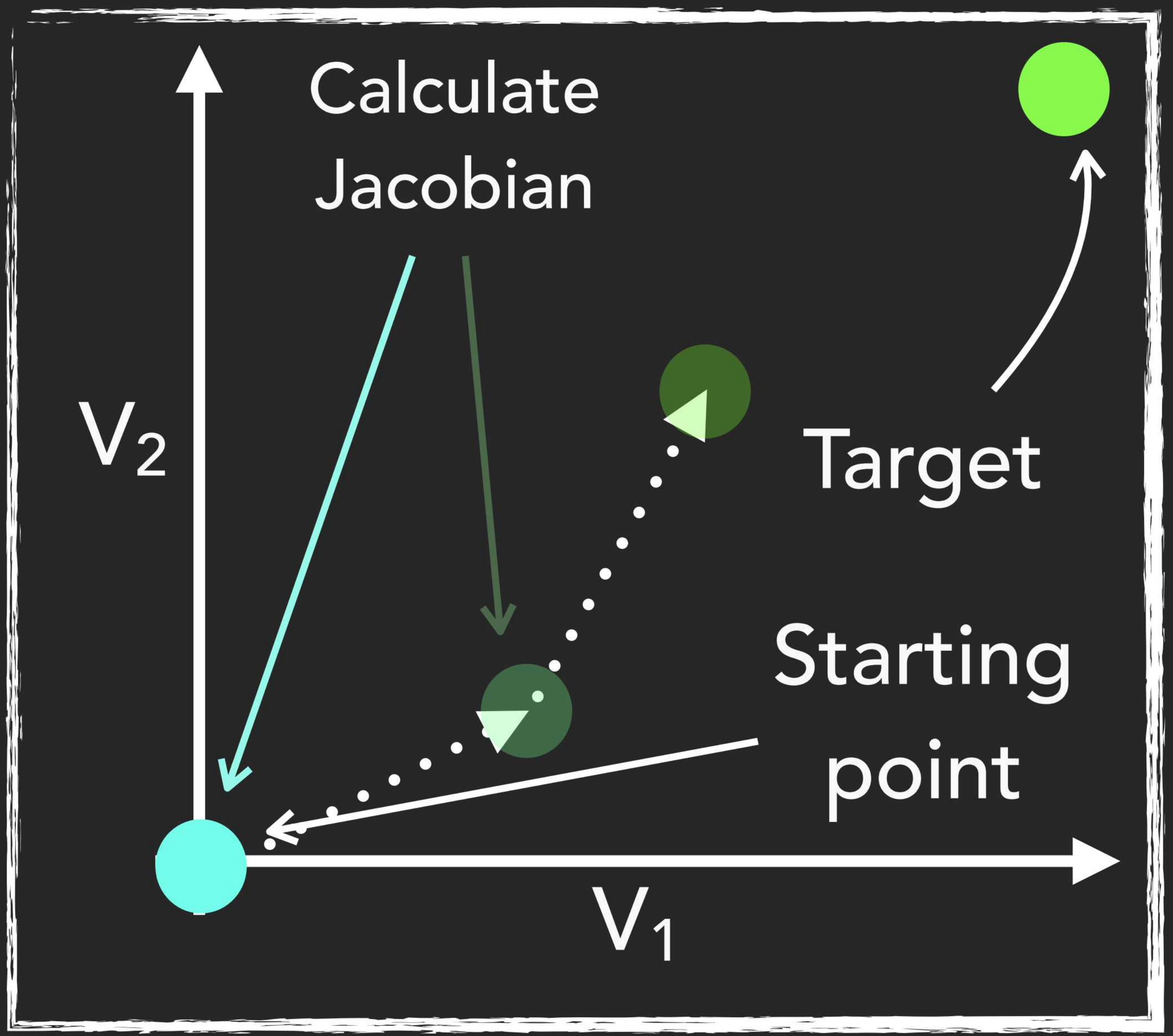

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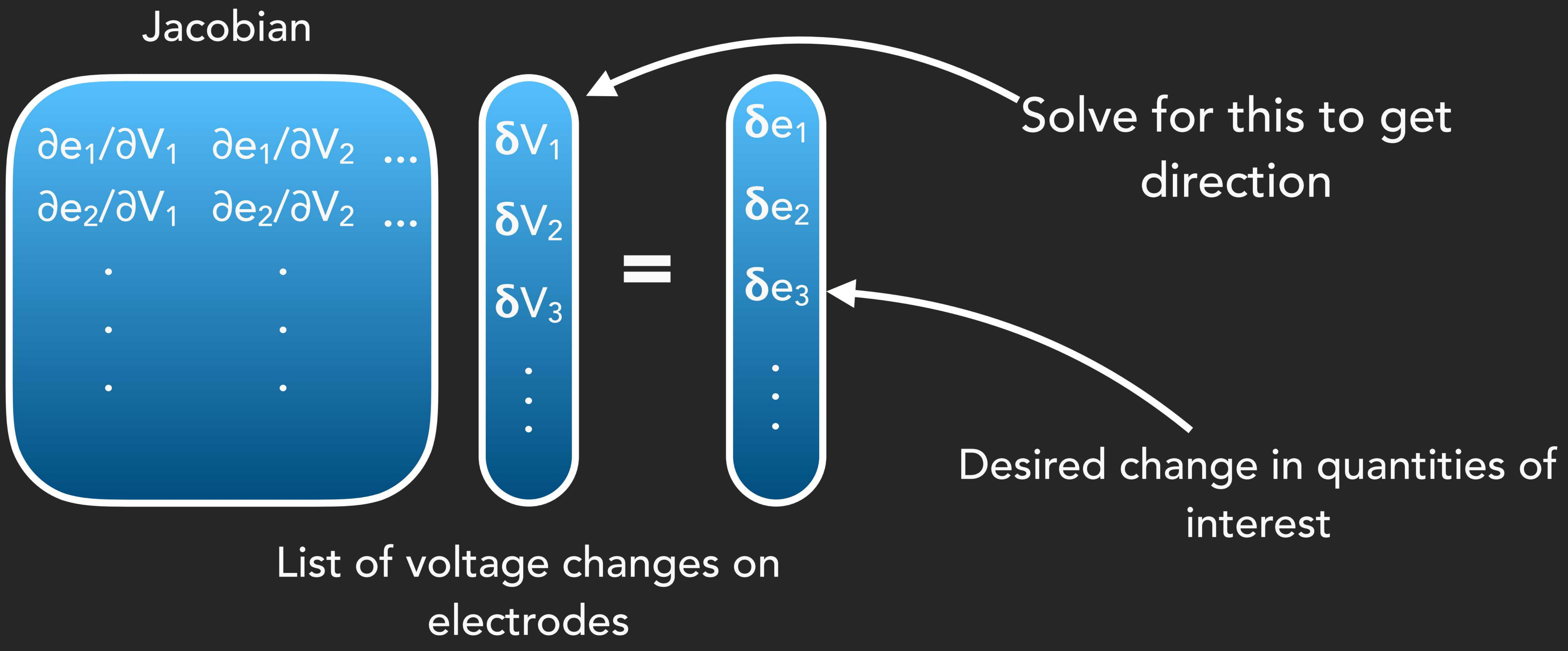

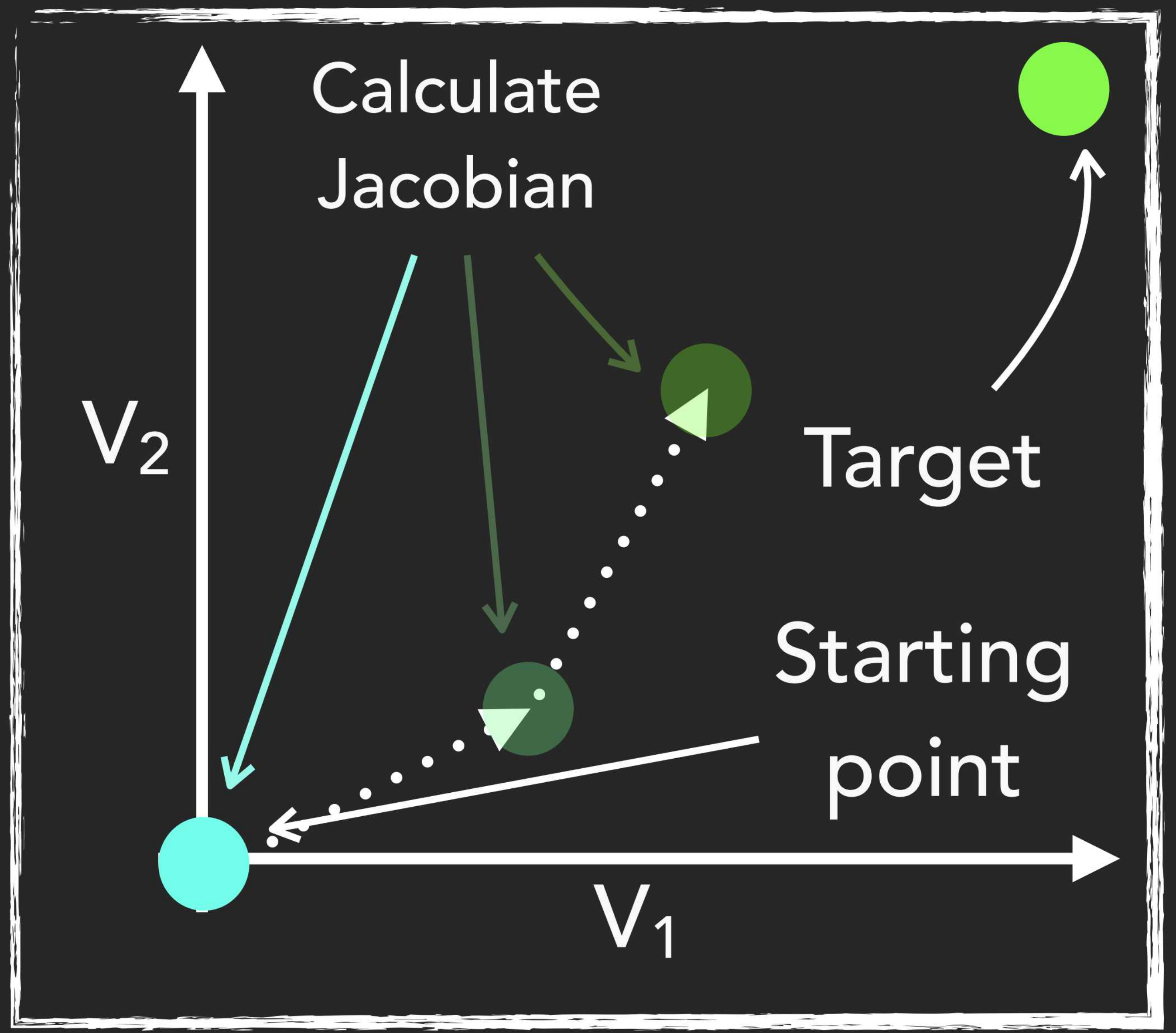

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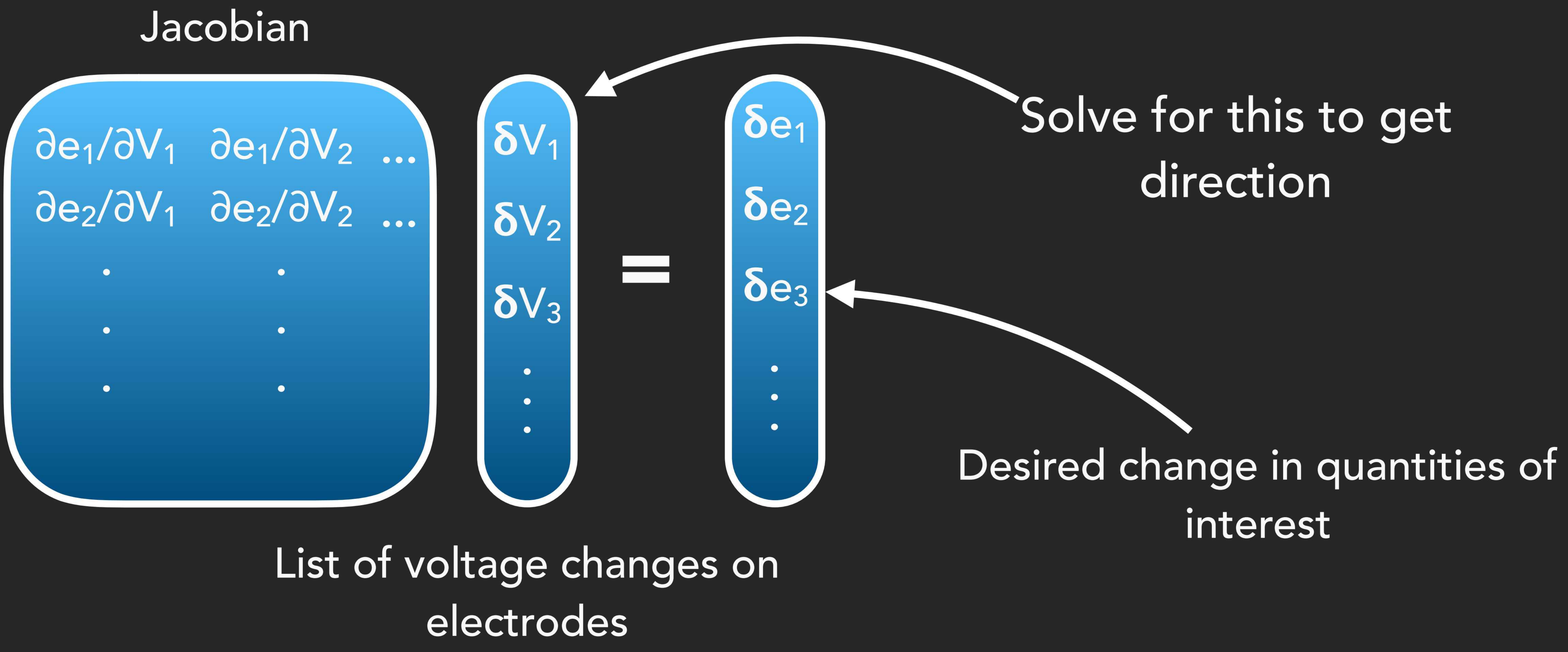

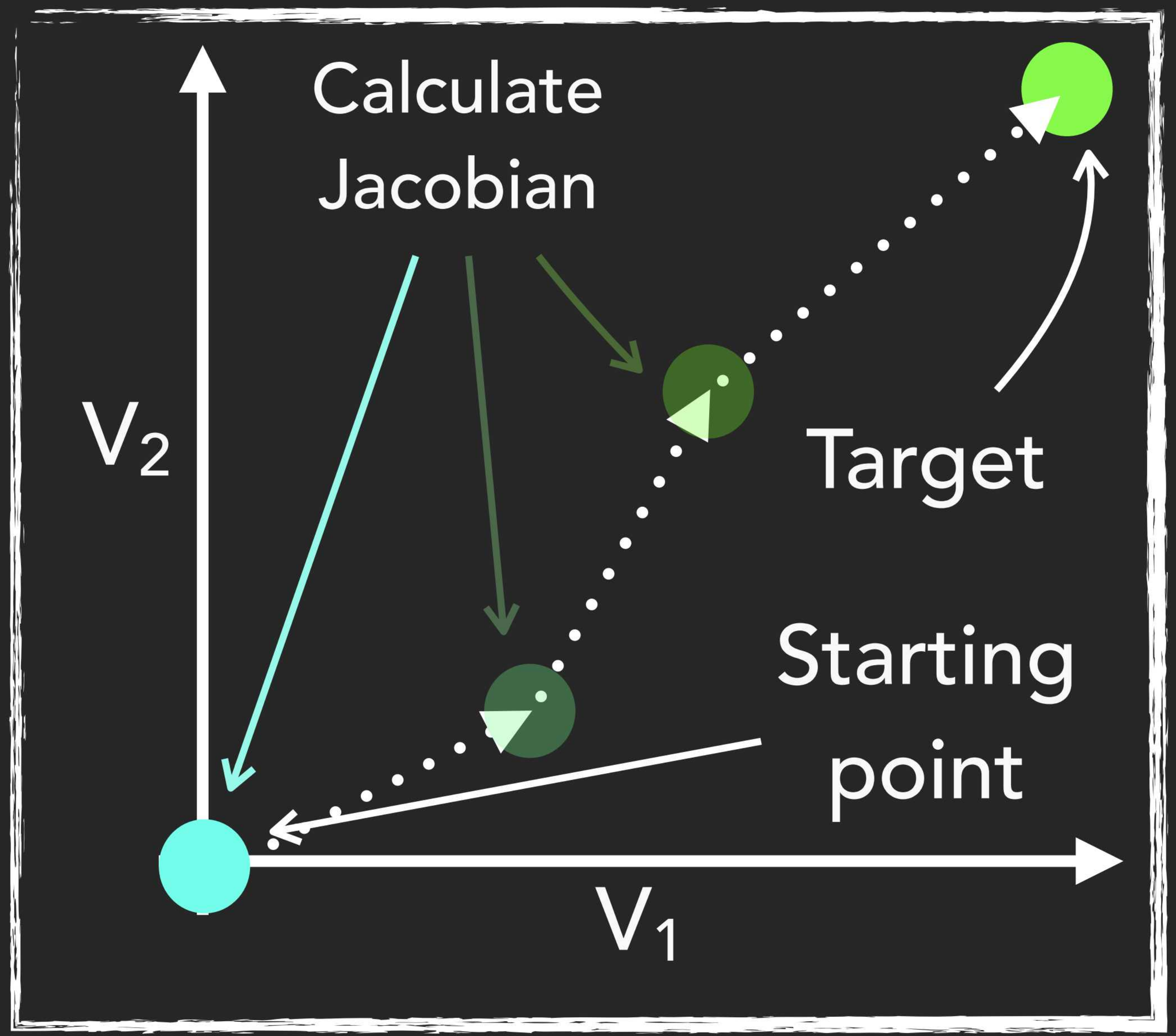

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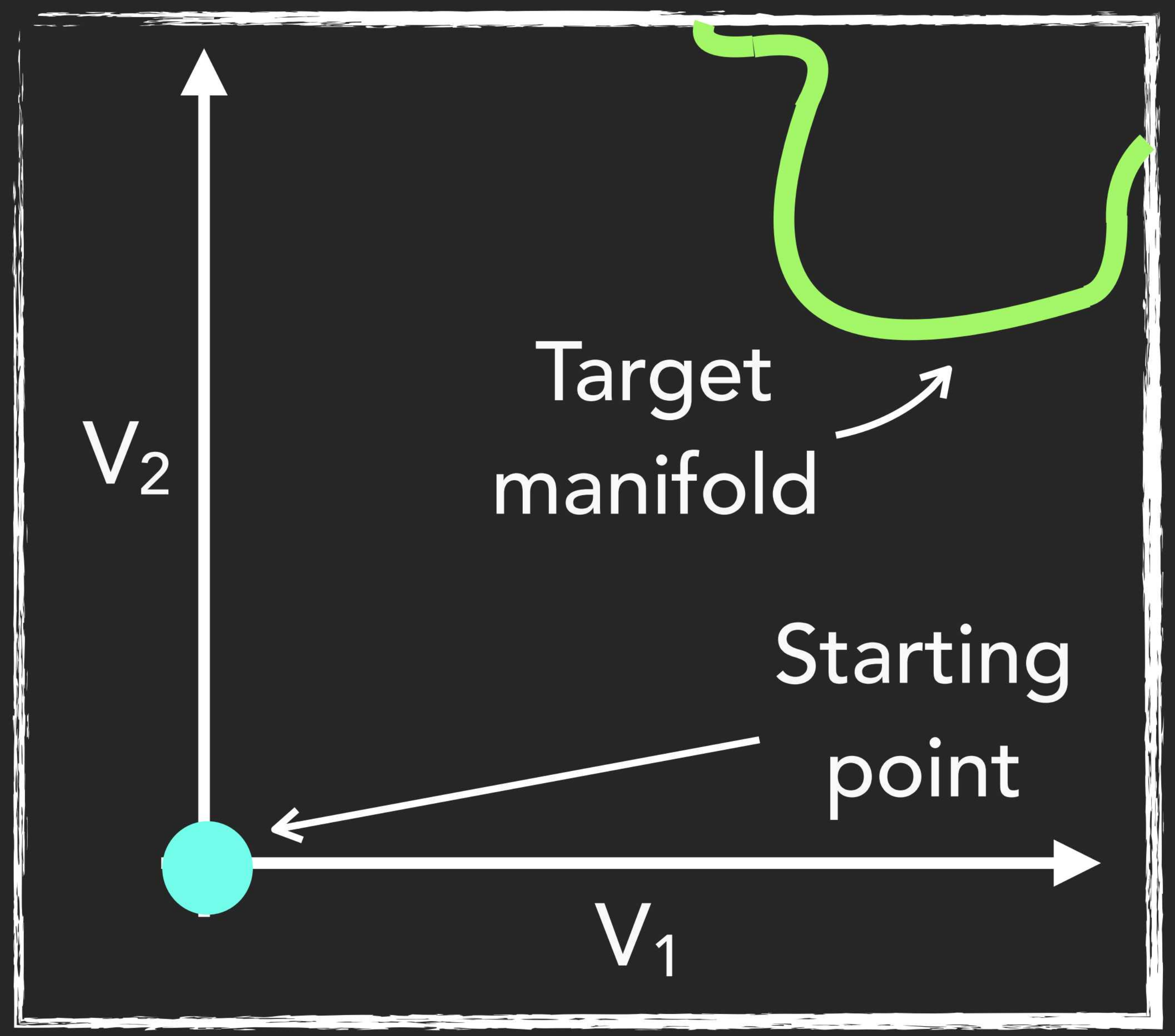

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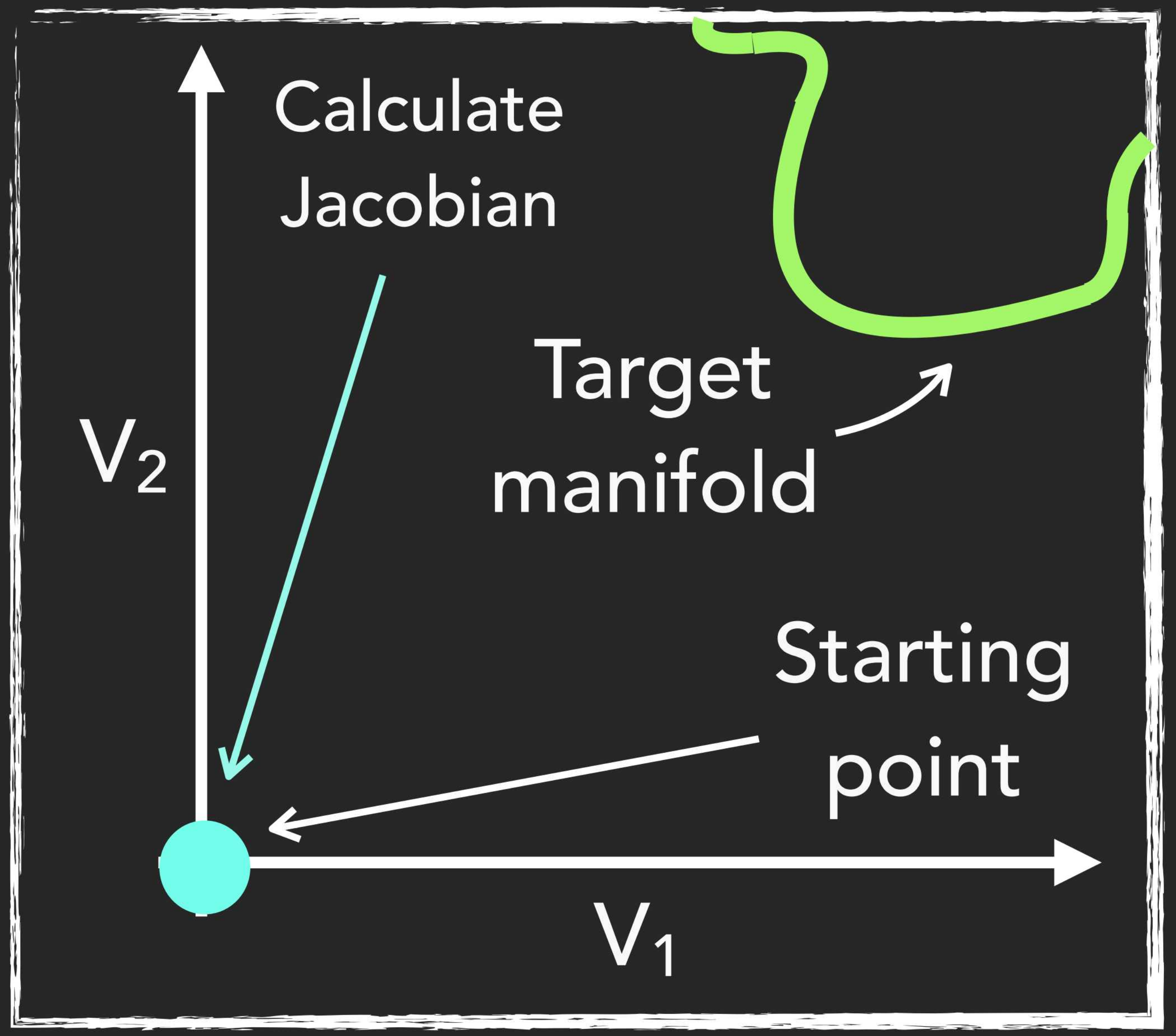

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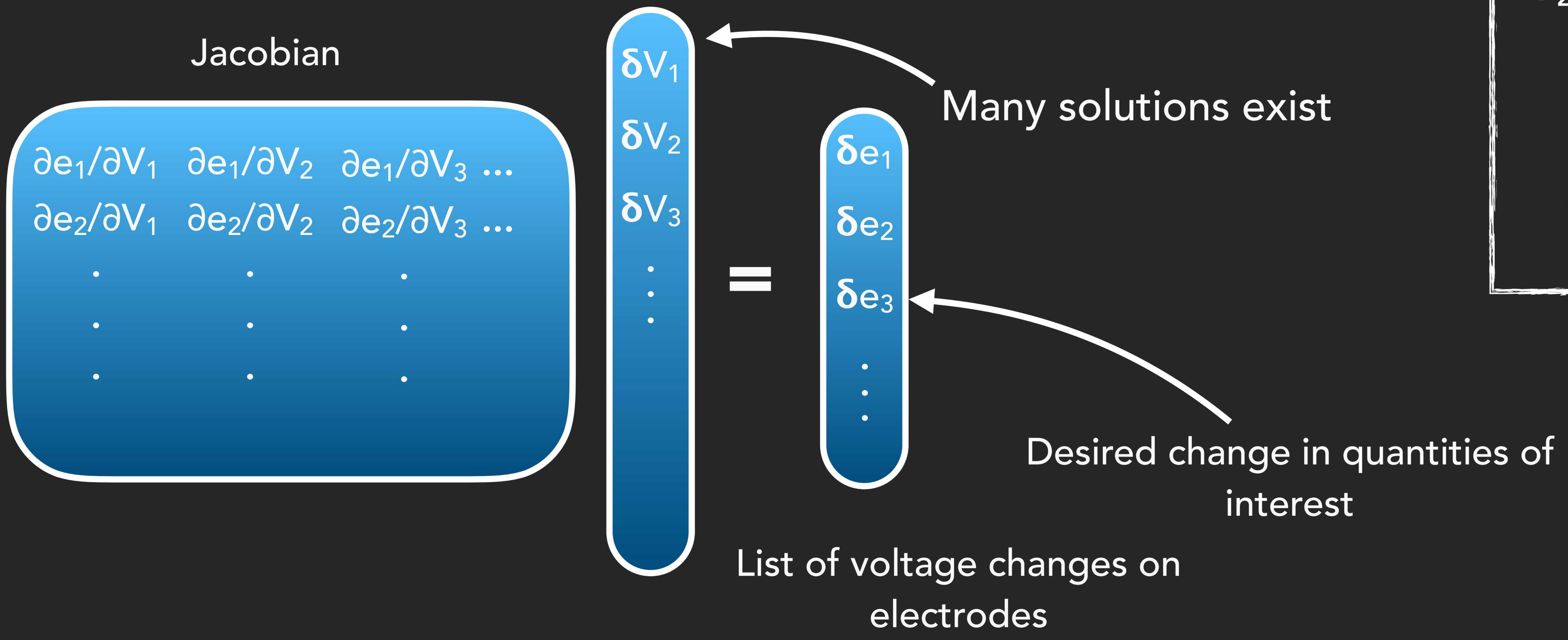

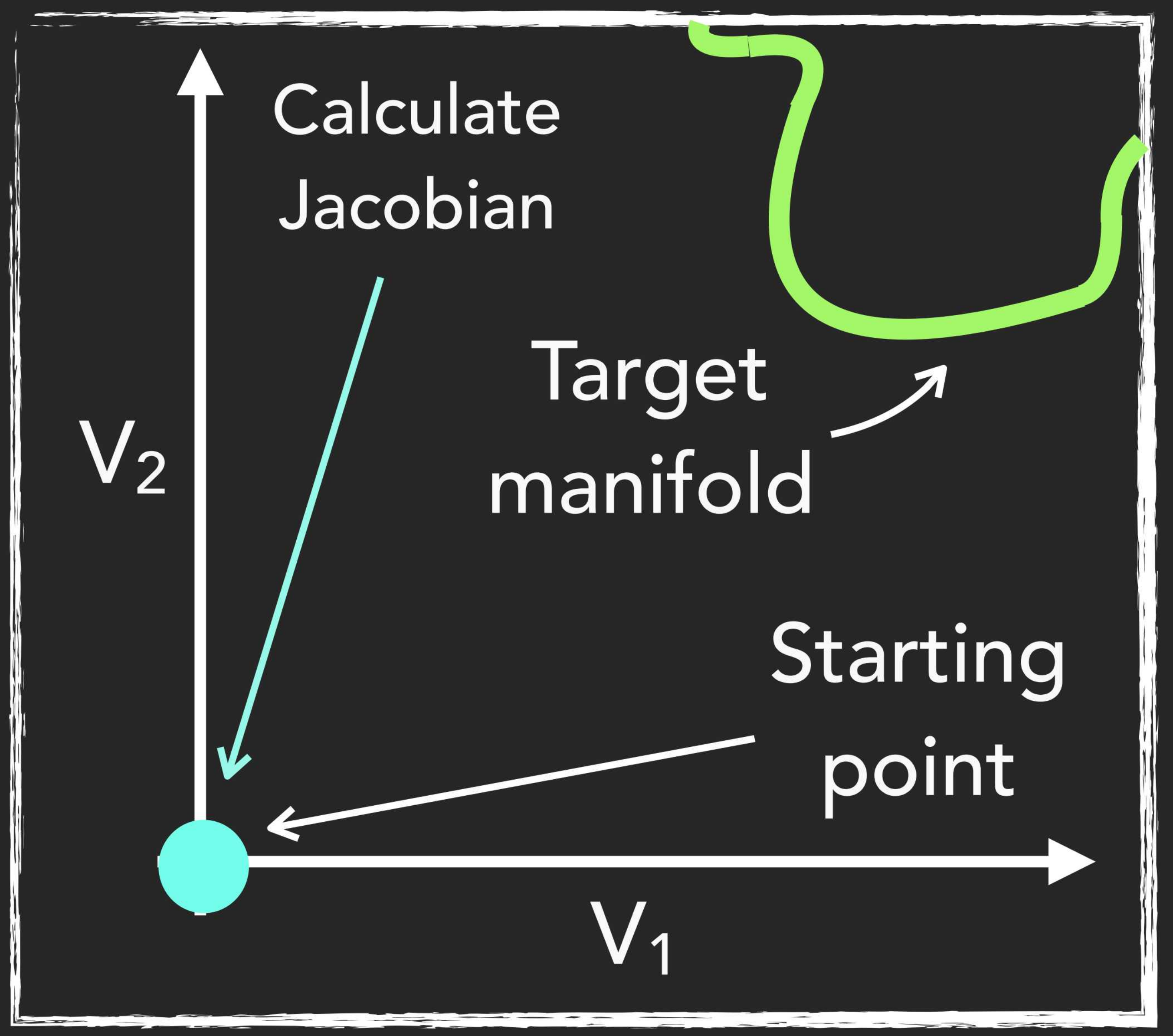

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Many solutions exist

Desired change in quantities of interest

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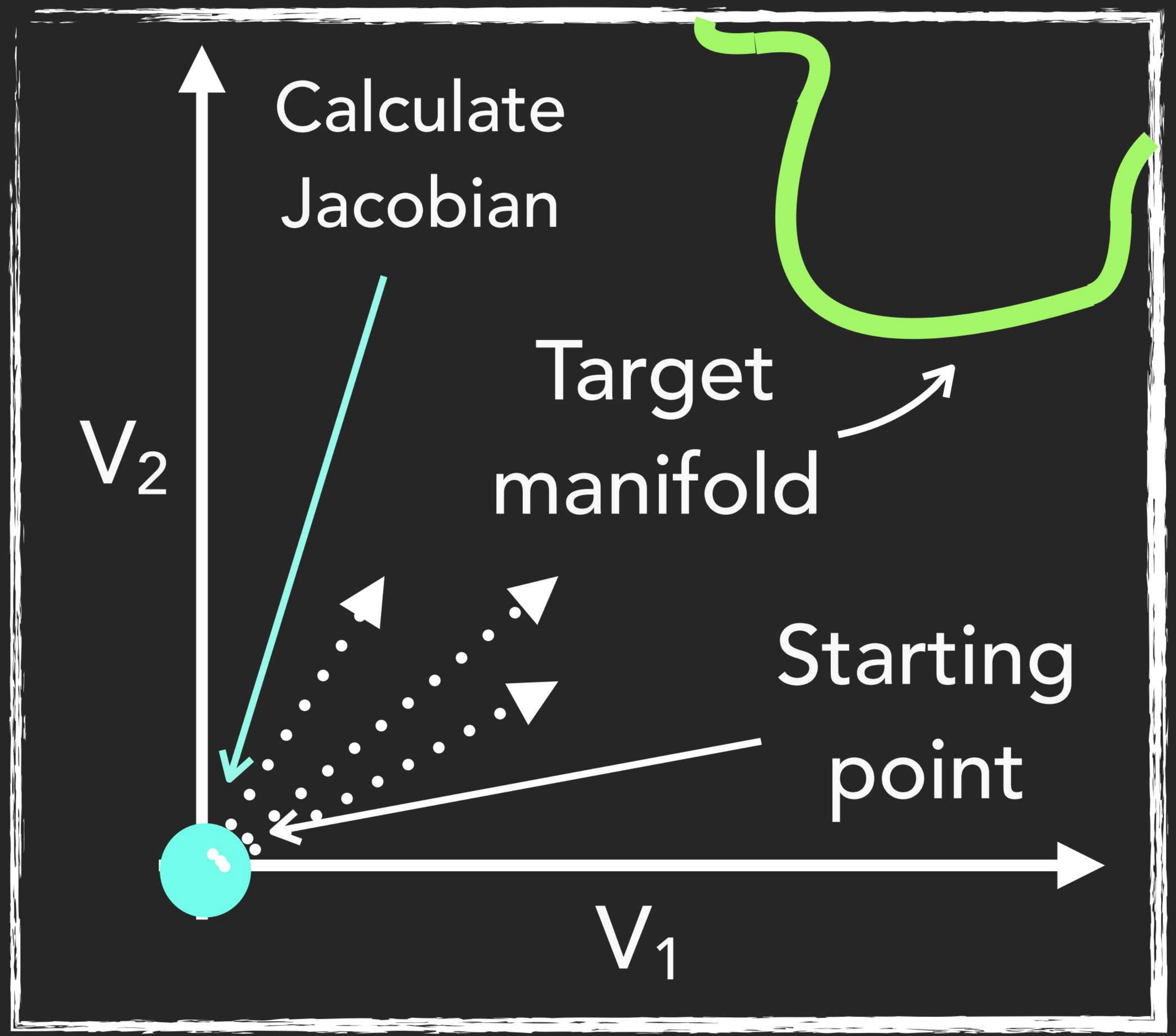

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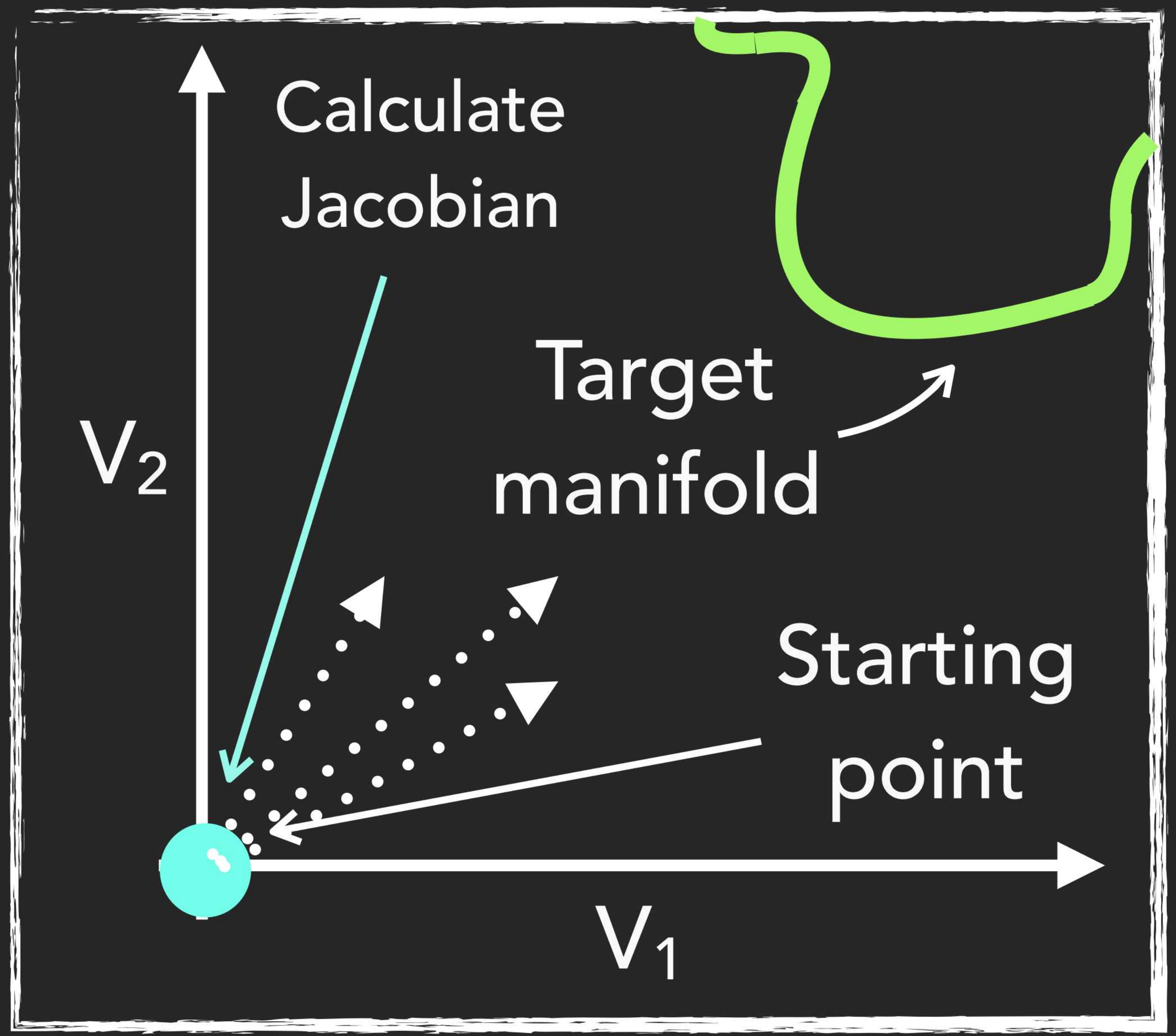
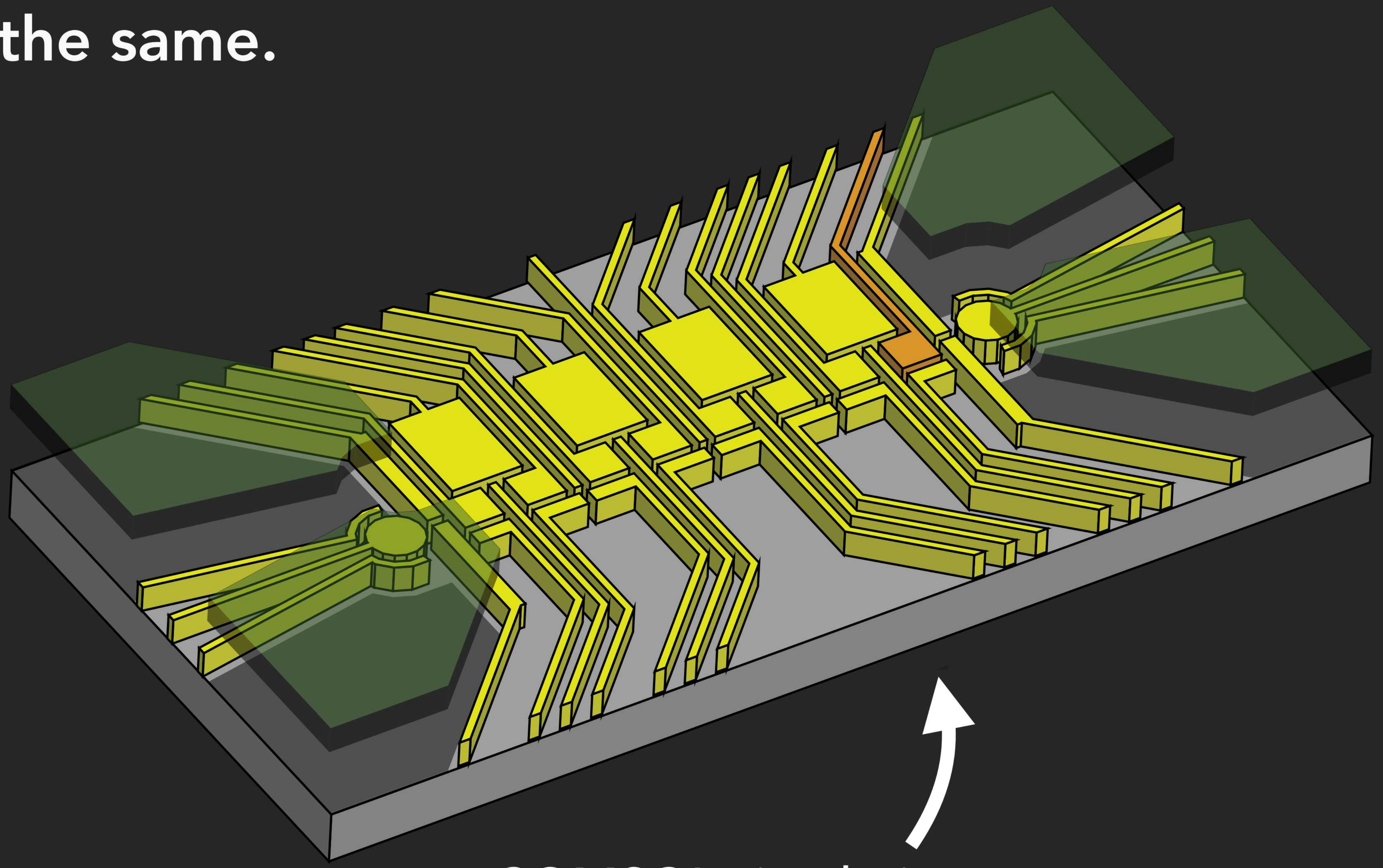


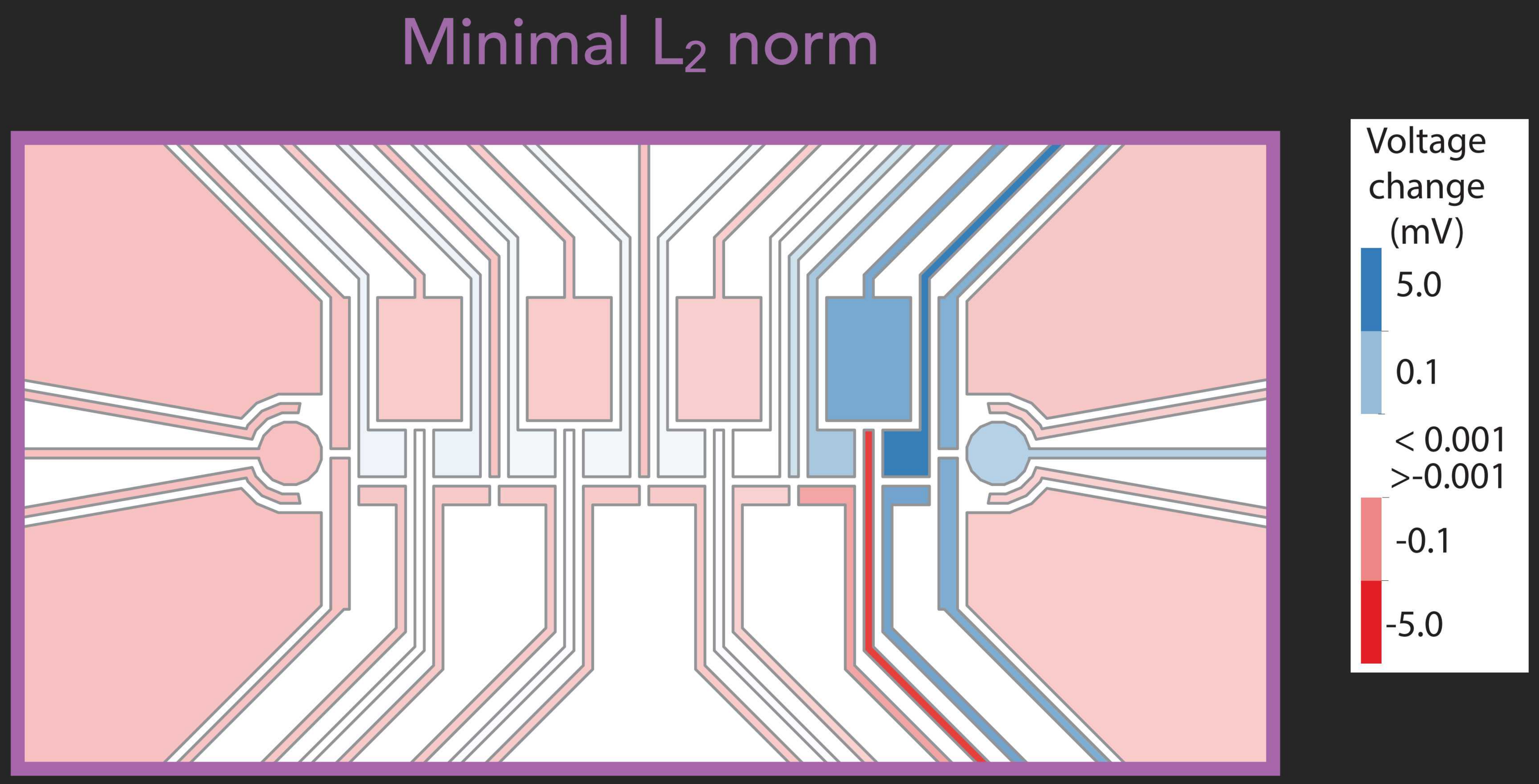
We want to find a tuning which limits the number of electrodes used.

Minimizing L_2 norm of voltages finds solutions which use many electrodes

Objective: add **one electron** to the right-most dot, keeping all tunnel couplings / other dot occupations **the same.**



COMSOL simulation.
Each dot contains one electron (calculated via Thomas-Fermi[1] approximation), each pair of dots have appreciable tunnel coupling (calculated using the WKB[2] approximation)



[1] Stopa, M. *Phys. Rev. B* **54**, 13767–13783 (1996).
[2] R. Shankar, *Principles of Quantum Mechanics*, 2nd ed (Springer, 1994)

L_1 regularization of underconstrained systems leads to sparse solutions

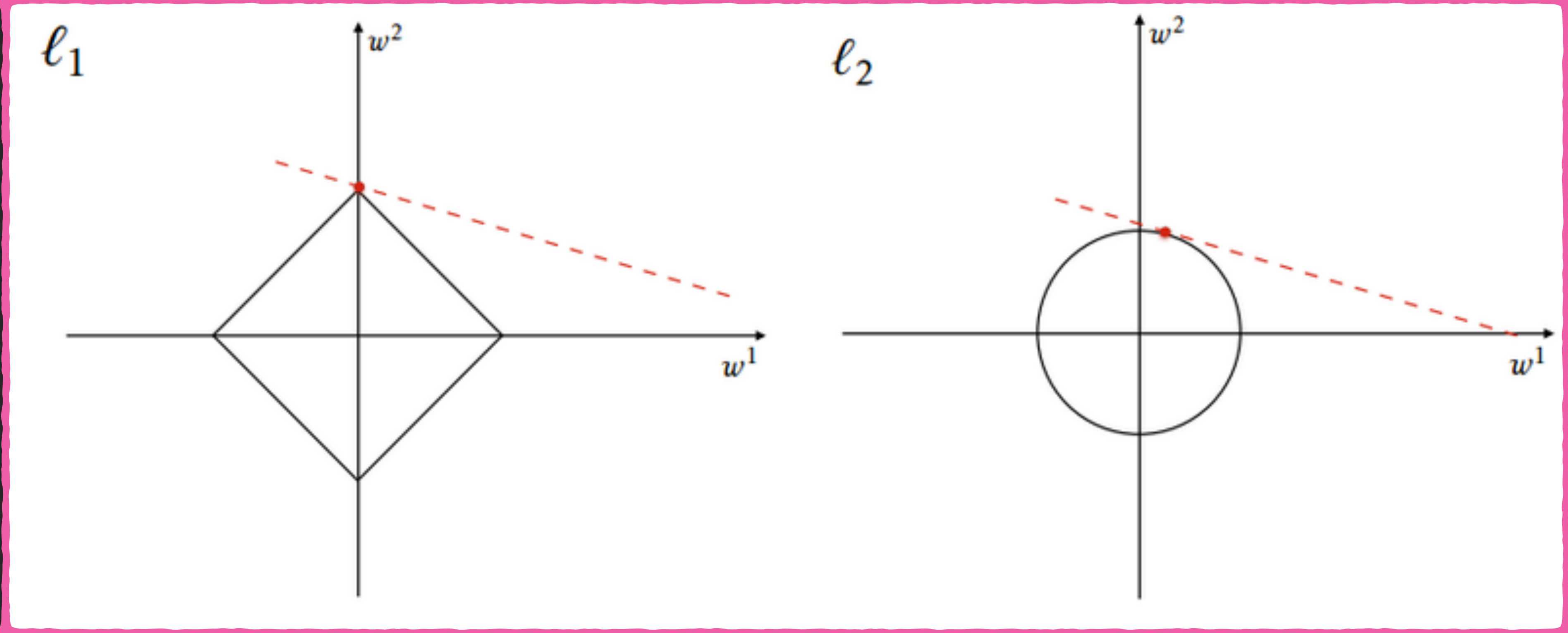
Regularization: finding the solution to an underconstrained linear system which minimizes a particular norm.

L_2 norm: $(x_1^2 + x_2^2 + x_3^2 + \ldots)^{1/2}$

L_1 norm: $(|x_1| + |x_2| + |x_3| + \ldots)$

L_0 norm: # of nonzero elements

L_1 regularization is a good proxy for L_0 regularization



Source: Wikipedia - "Regularization (mathematics)"

Compressed sensing techniques can be used to find voltage tuning with minimal L_1 norm

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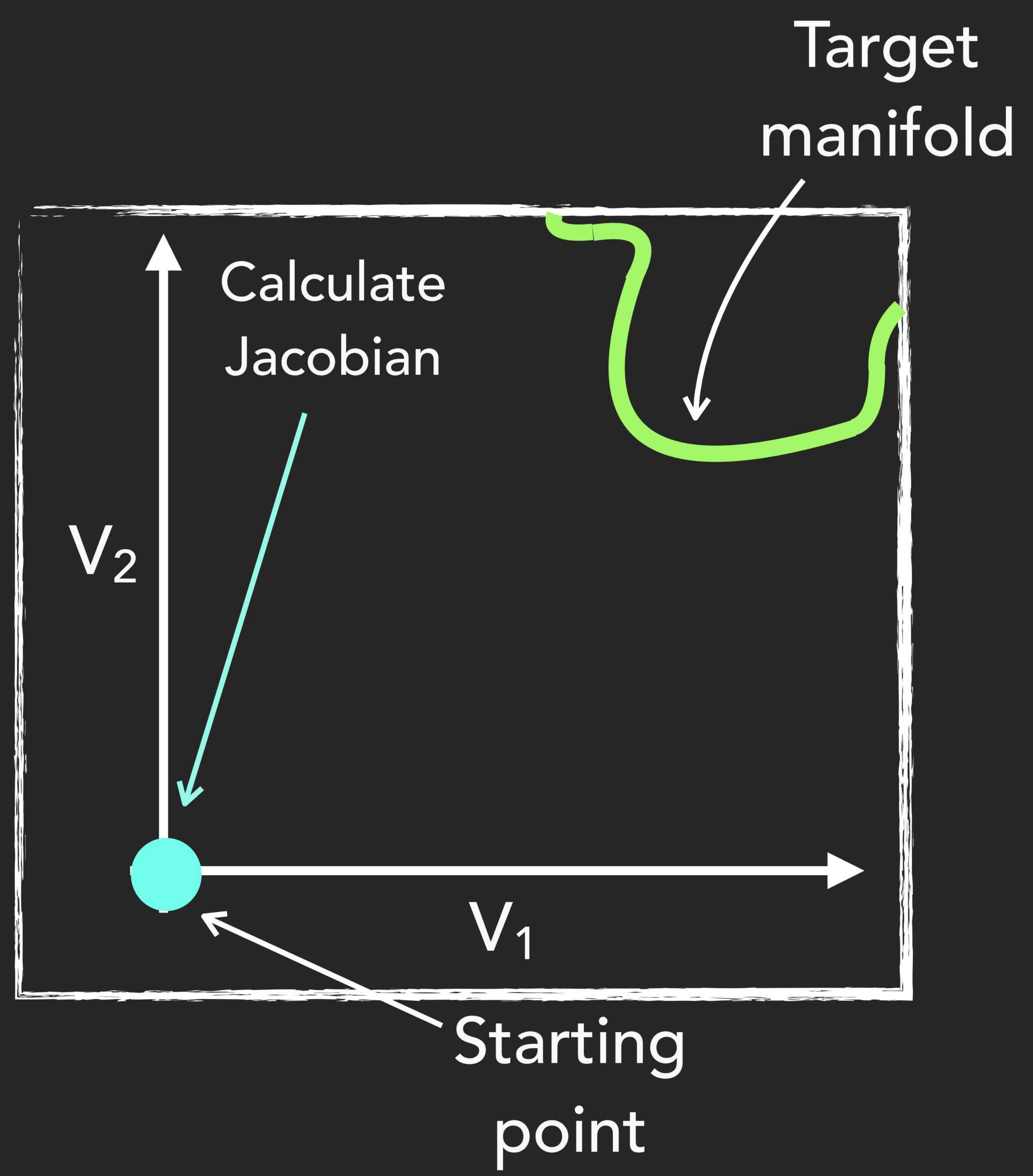

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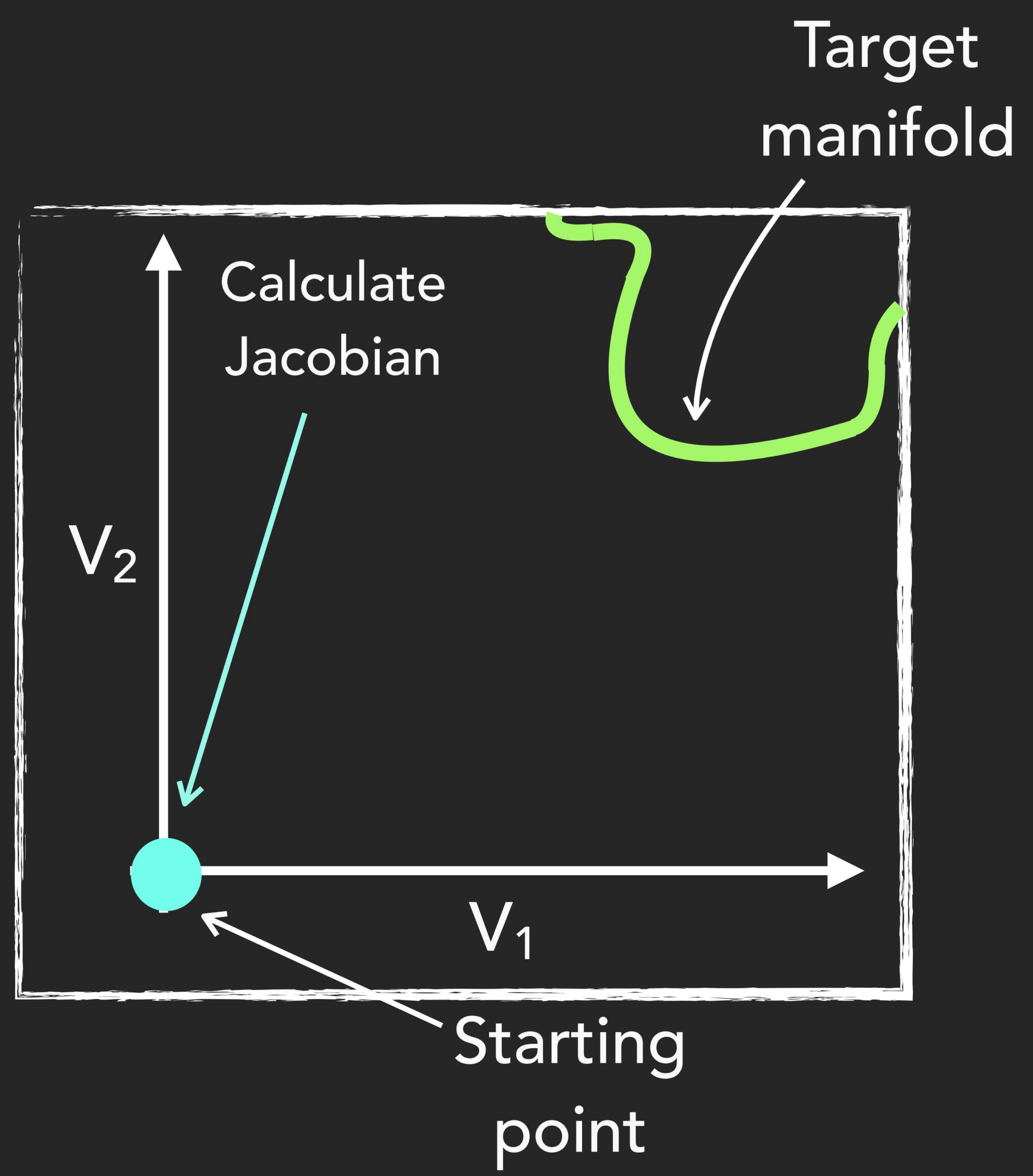

[1] E. J. Candès, et al., Communications on Pure and Applied Mathematics, **59**, 1207 (2006)
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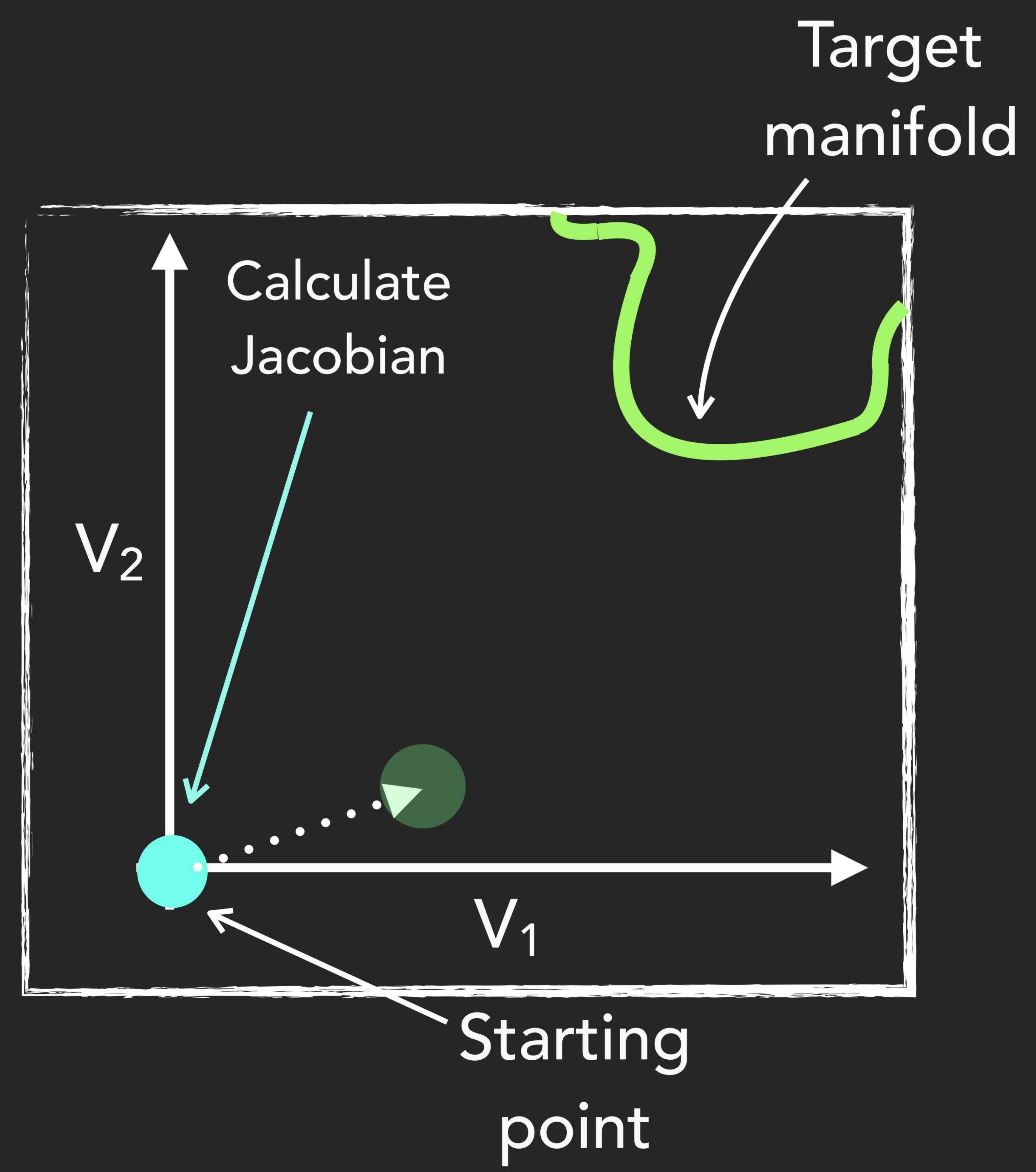

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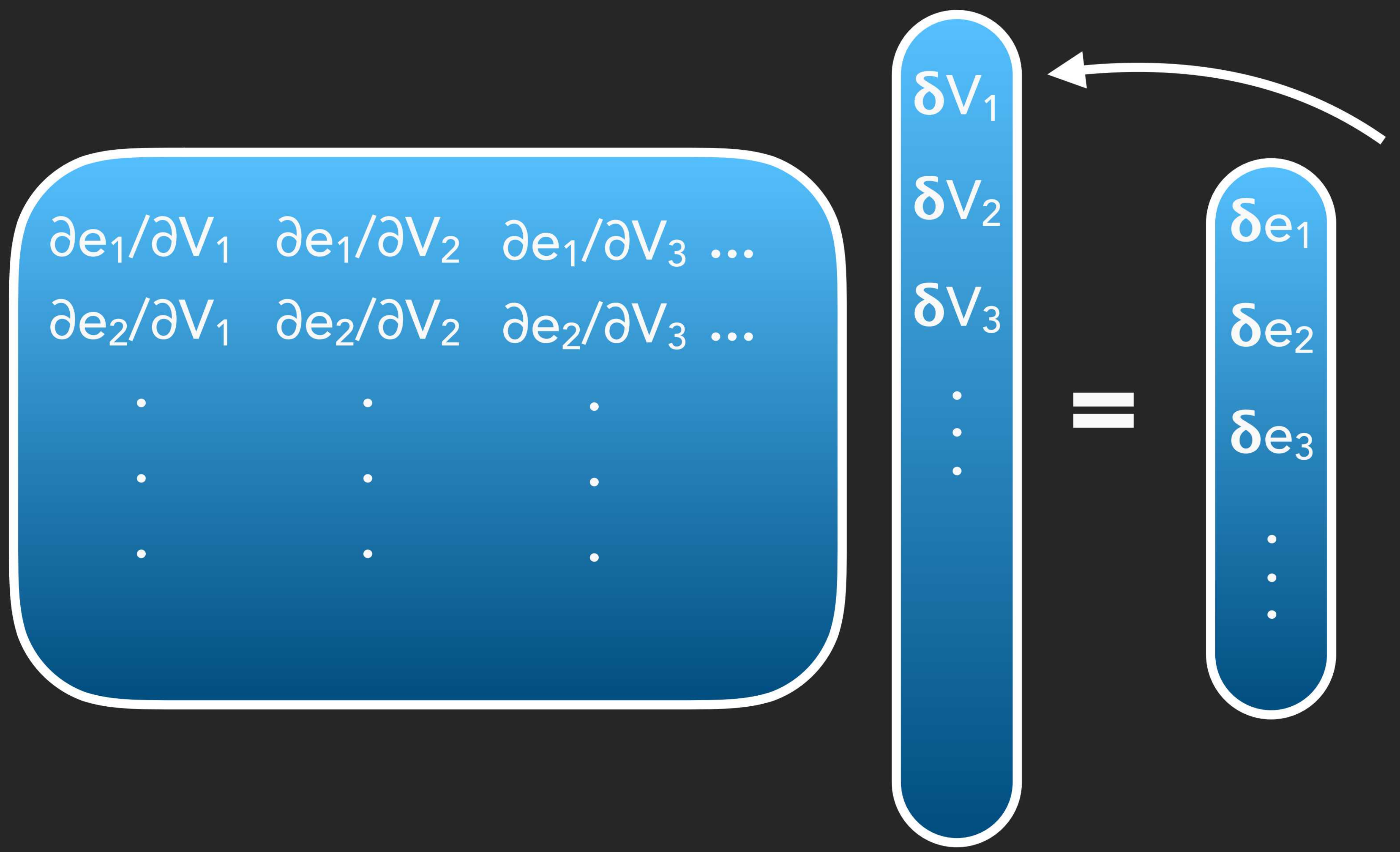

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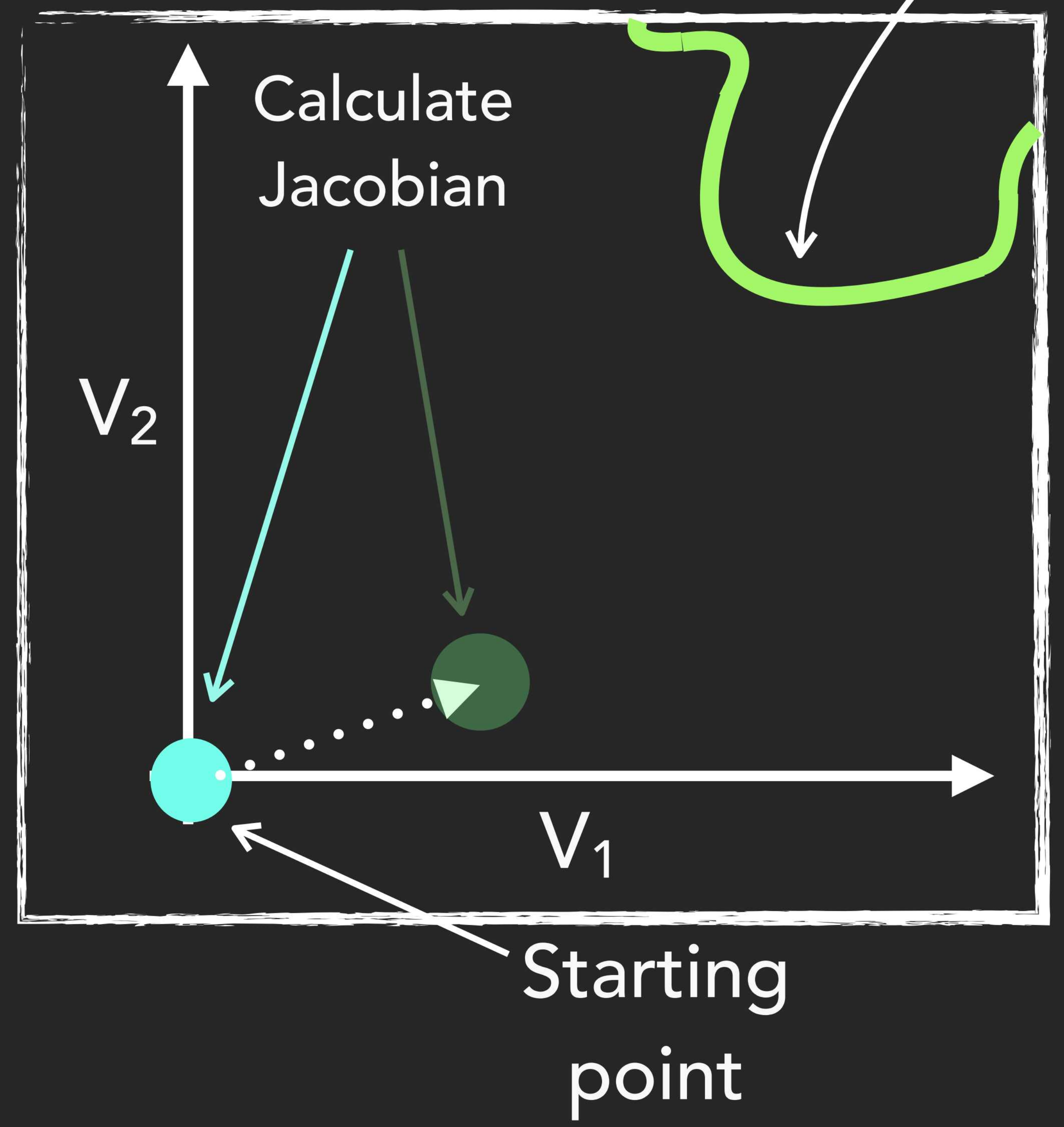

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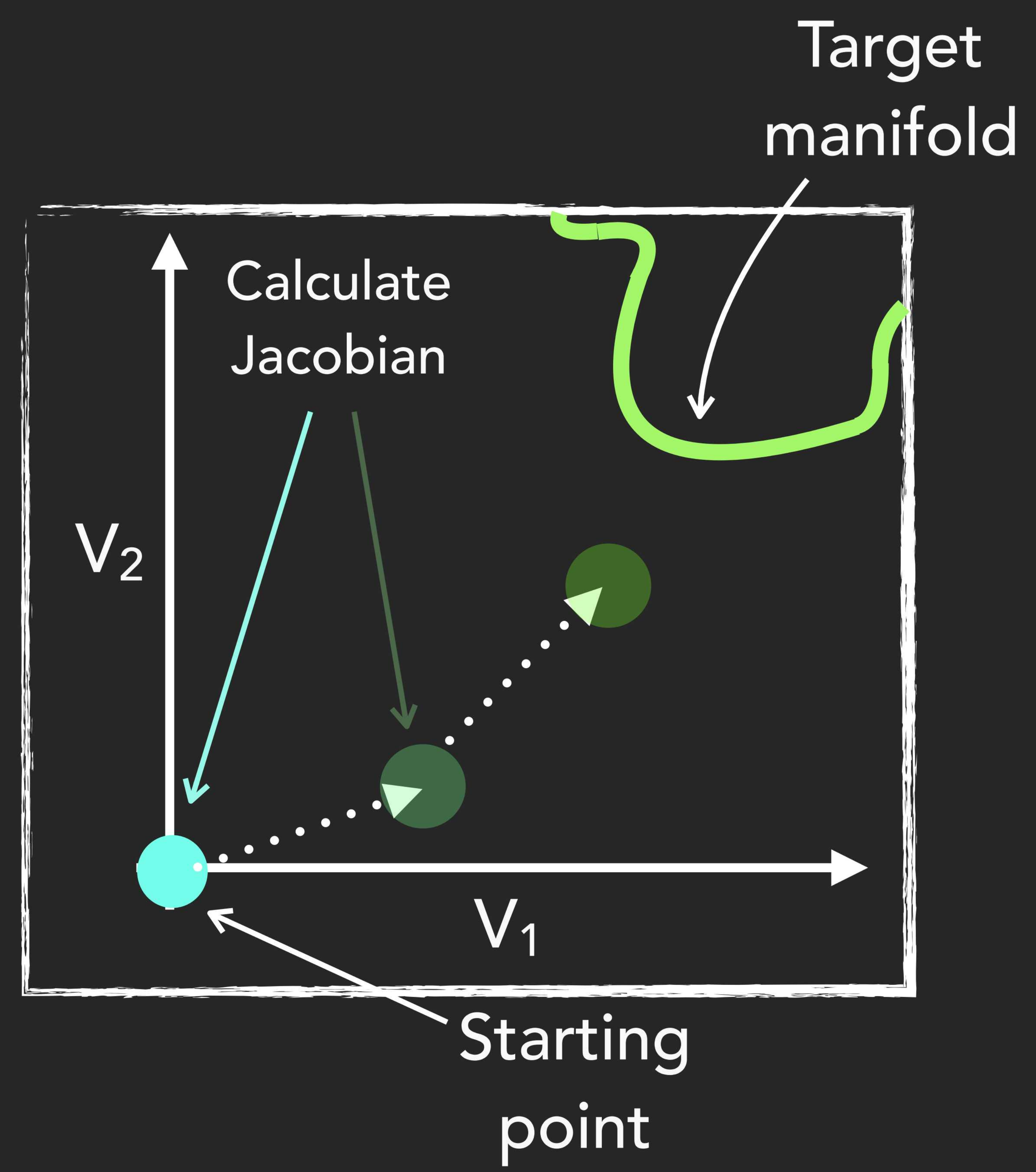
[2] D. Donoho, IEEE Transactions on Information Theory, **52**, 1289 (2006)
[3] Diamond, S. & Boyd, S. CVXpy Journal of Machine Learning Research **17**, 1–5 (2016)

Compressed sensing techniques can be used to find voltage tuning with minimal L_1 norm

Given a nonlinear function that relates the voltages on ~~n~~ ***m>n*** electrodes to ***n*** quantities of interest (i.e. dot occupations, dot energies, tunnel couplings), find voltages which yield operational target (desired dot occupations, dot energies, tunnel couplings).

$$\begin{pmatrix} \partial e_1/\partial V_1 & \partial e_1/\partial V_2 & \partial e_1/\partial V_3 & \cdots \\ \partial e_2/\partial V_1 & \partial e_2/\partial V_2 & \partial e_2/\partial V_3 & \cdots \\ \vdots & \vdots & \vdots & \end{pmatrix} \begin{pmatrix} \delta V_1 \\ \delta V_2 \\ \delta V_3 \\ \vdots \end{pmatrix} = \begin{pmatrix} \delta e_1 \\ \delta e_2 \\ \delta e_3 \\ \vdots \end{pmatrix}$$

Using methods from compressed sensing[1-3], we can find the solution which minimizes the L_1 norm



[1] E. J. Candès, et al., Communications on Pure and Applied Mathematics, **59**, 1207 (2006)
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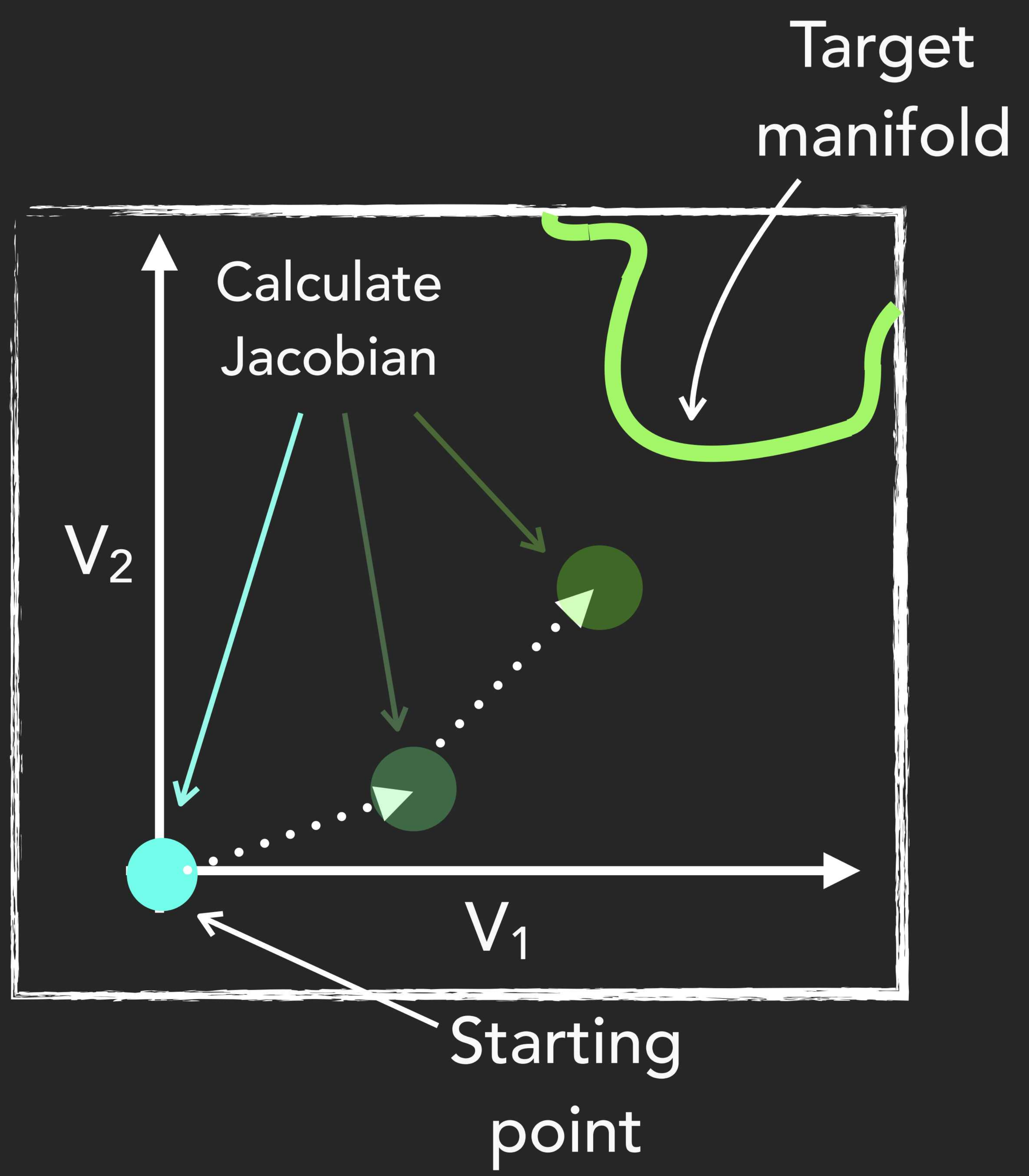

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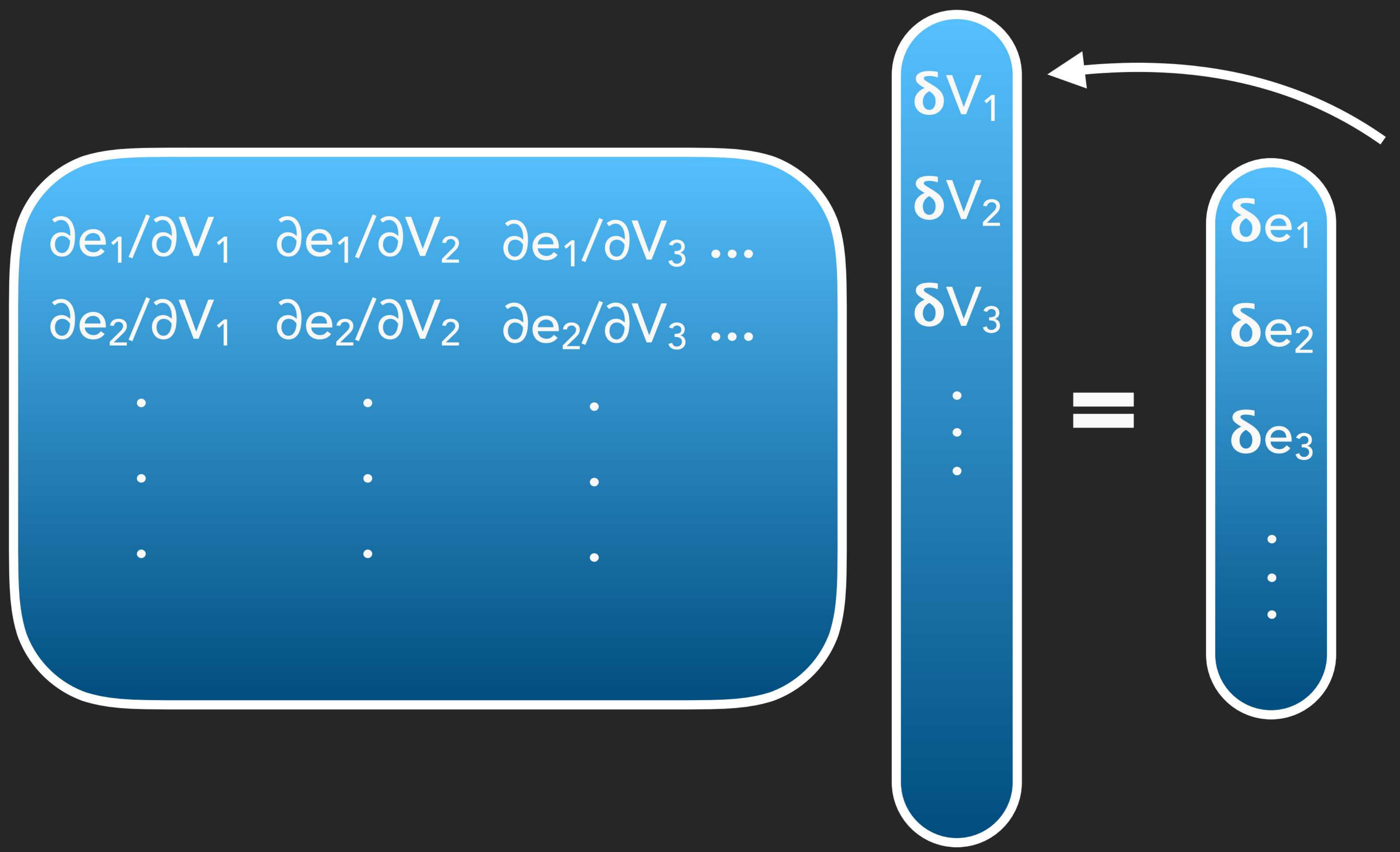

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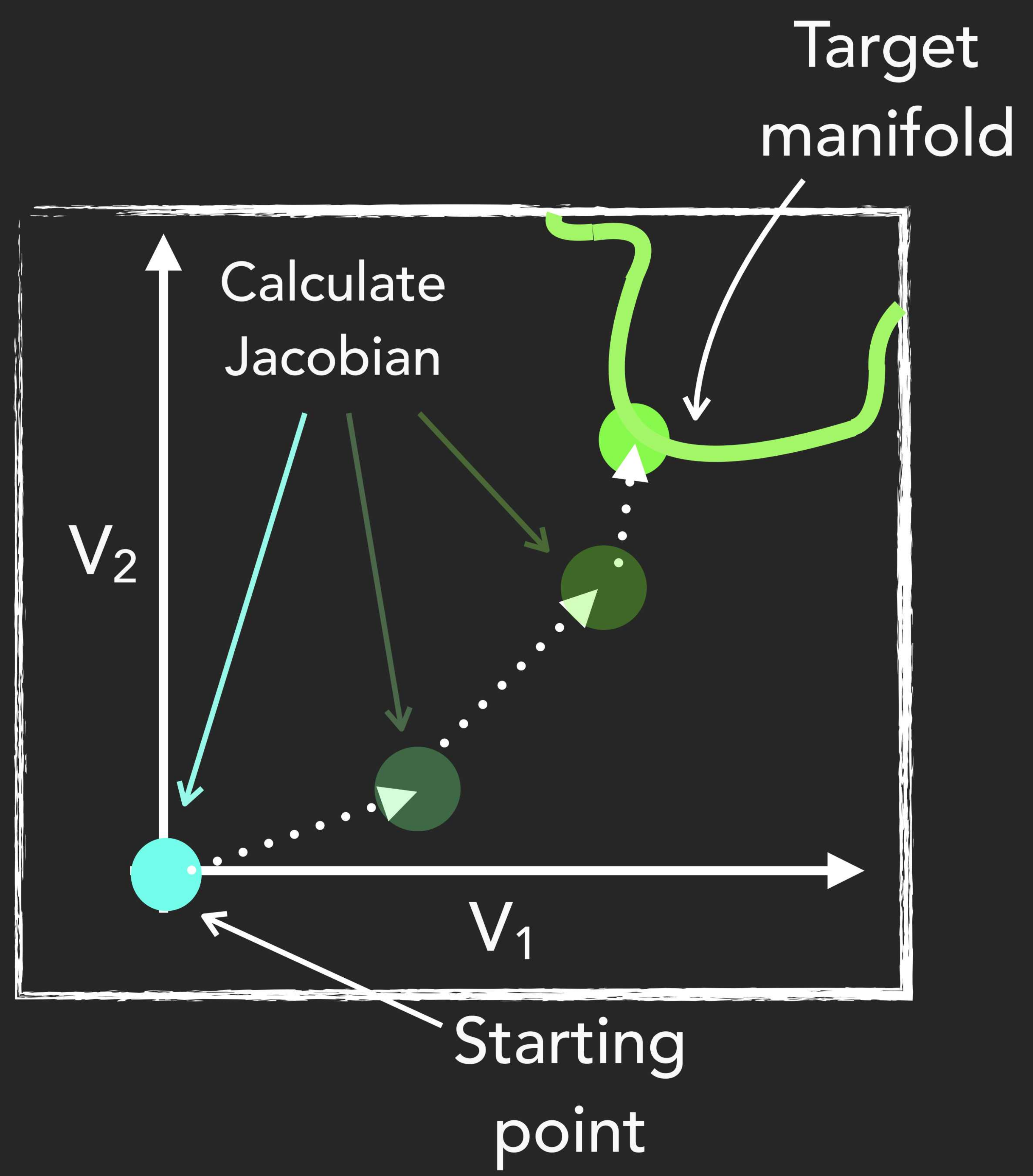

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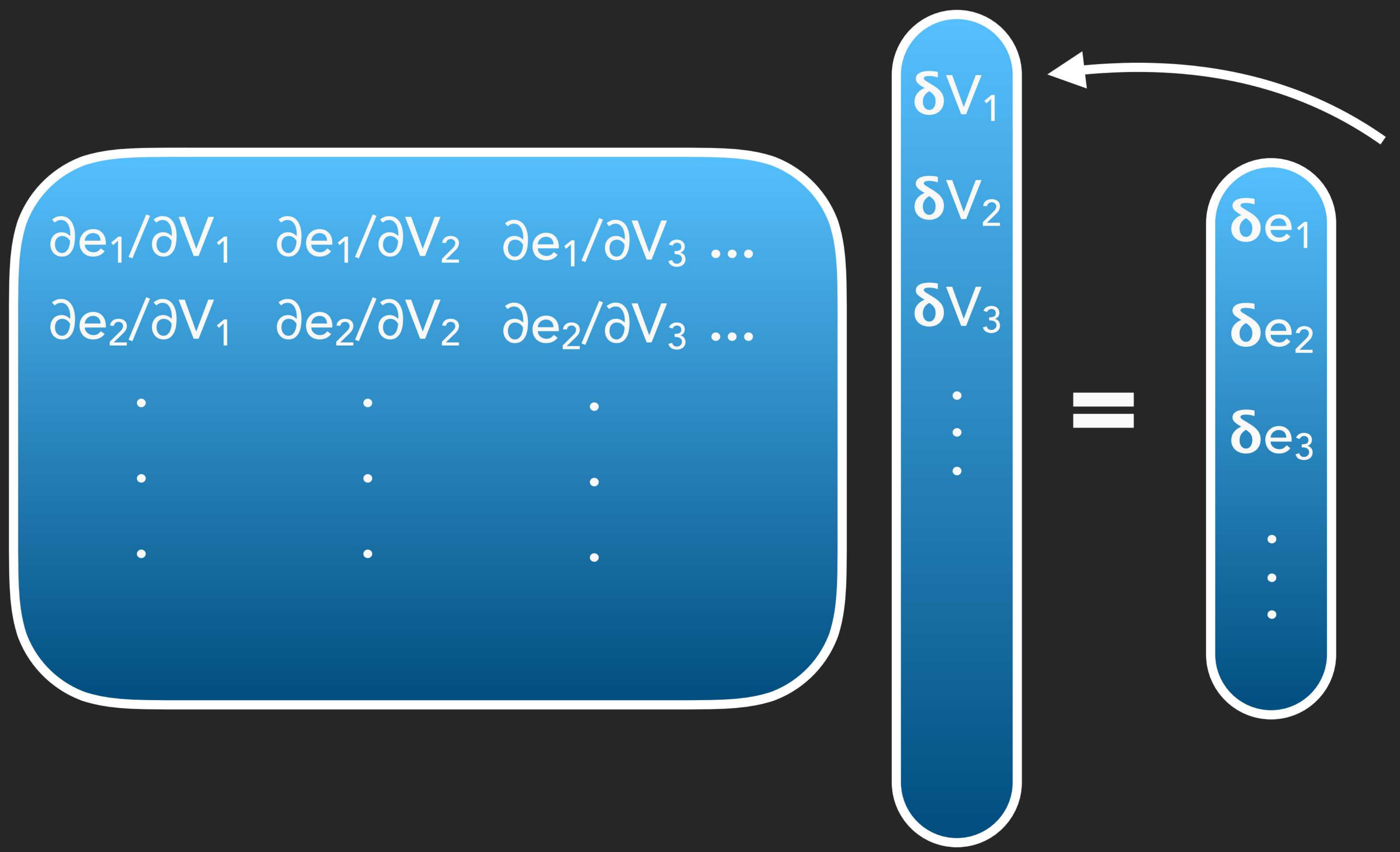

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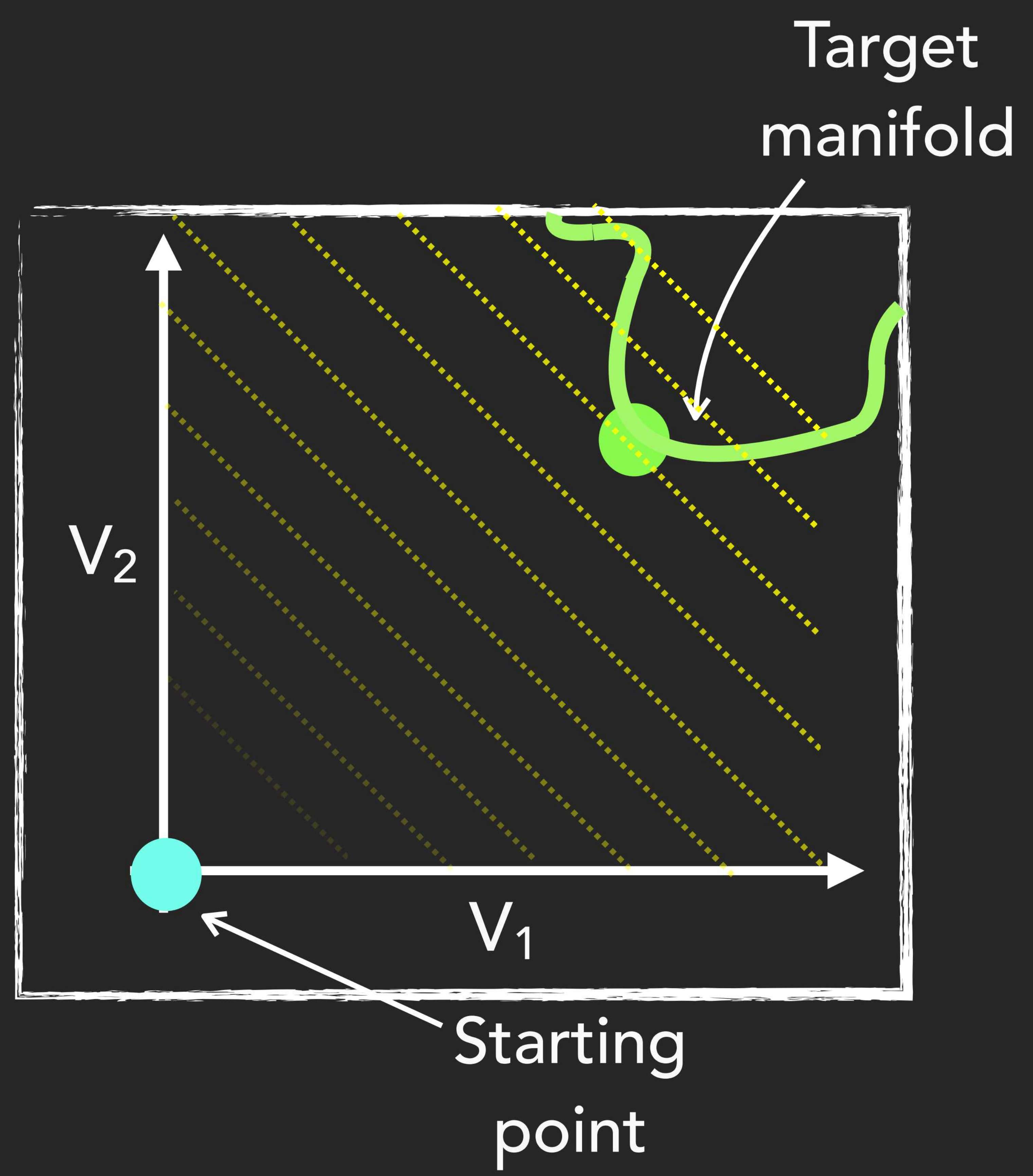

The solution chosen is guaranteed to be at a local minimum of the L_1 norm

[1] E. J. Candès, et al., Communications on Pure and Applied Mathematics, **59**, 1207 (2006)
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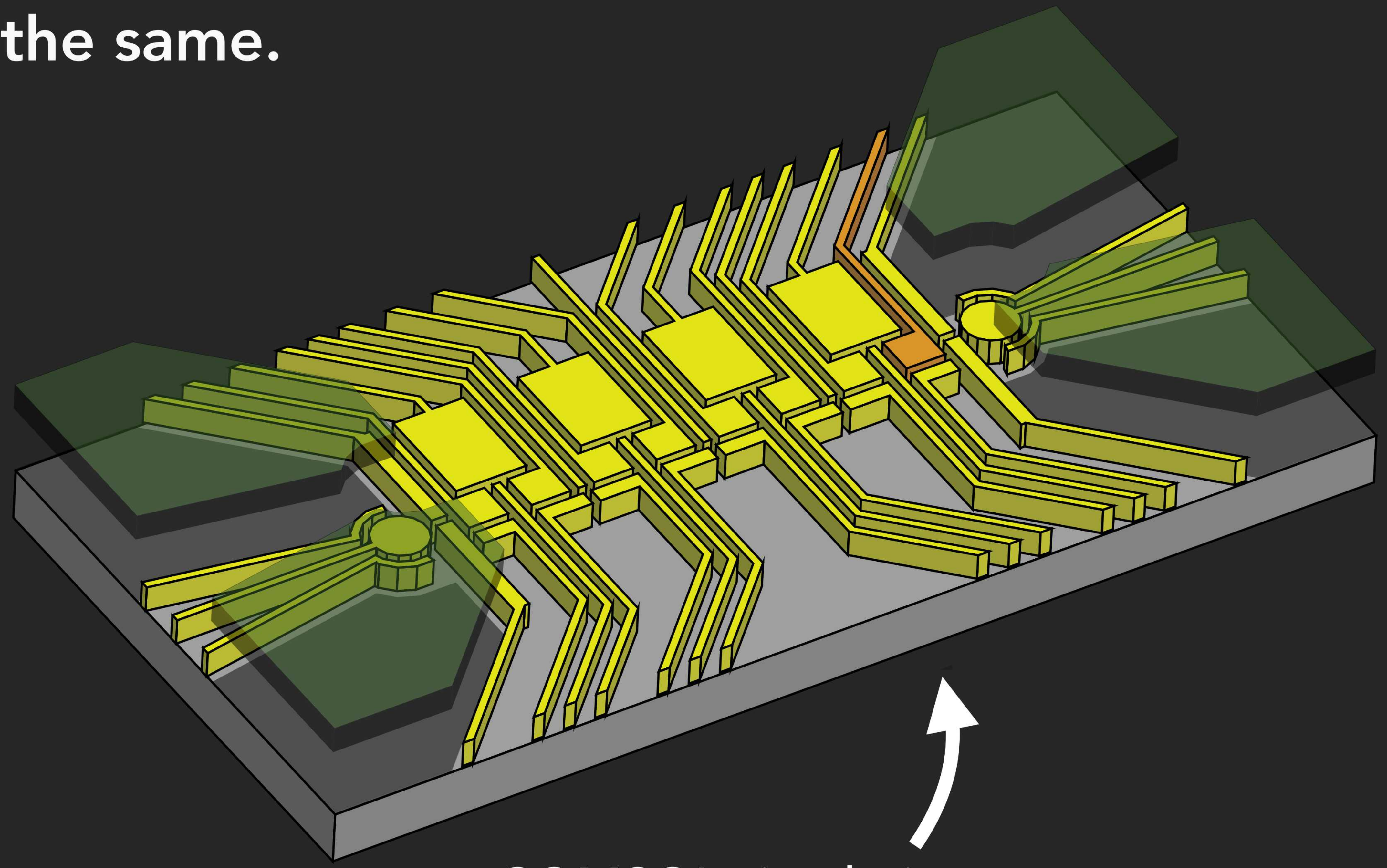
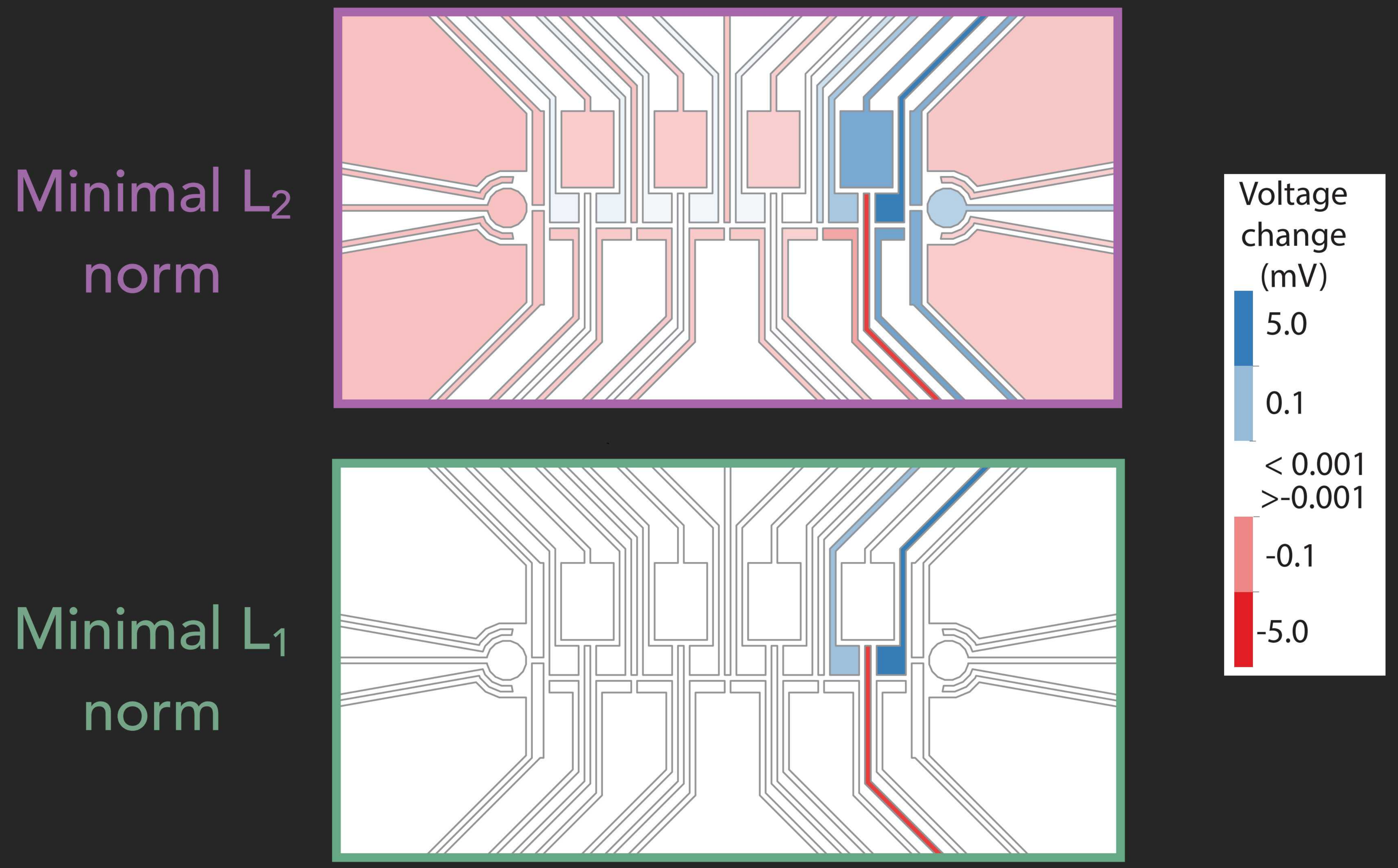
Minimizing L_1 norm of voltages ensures small voltages on limited number of gates

Objective: add **one electron** to the right-most dot, keeping all tunnel couplings / other dot occupations **the same.**



COMSOL simulation.
Each dot contains one electron (calculated via Thomas-Fermi[1] approximation), each pair of dots have appreciable tunnel coupling (calculated using the WKB[2] approximation)



The solution with the minimal L_1 norm will have ***small voltages*** on a ***limited number of gates***

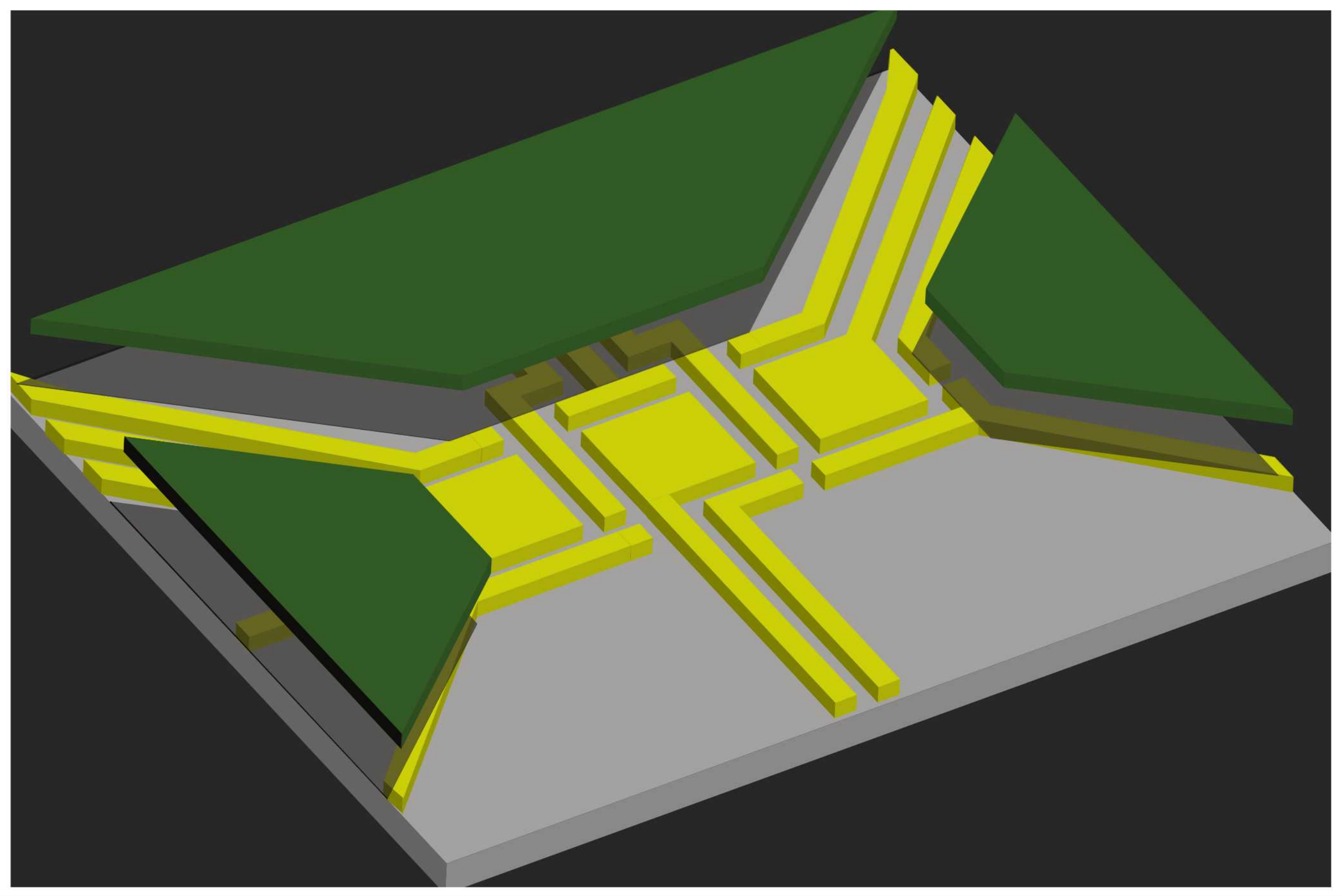
[1] Stopa, M. *Phys. Rev. B* **54**, 13767–13783 (1996).
[2] R. Shankar, *Principles of Quantum Mechanics*, 2nd ed (Springer, 1994)

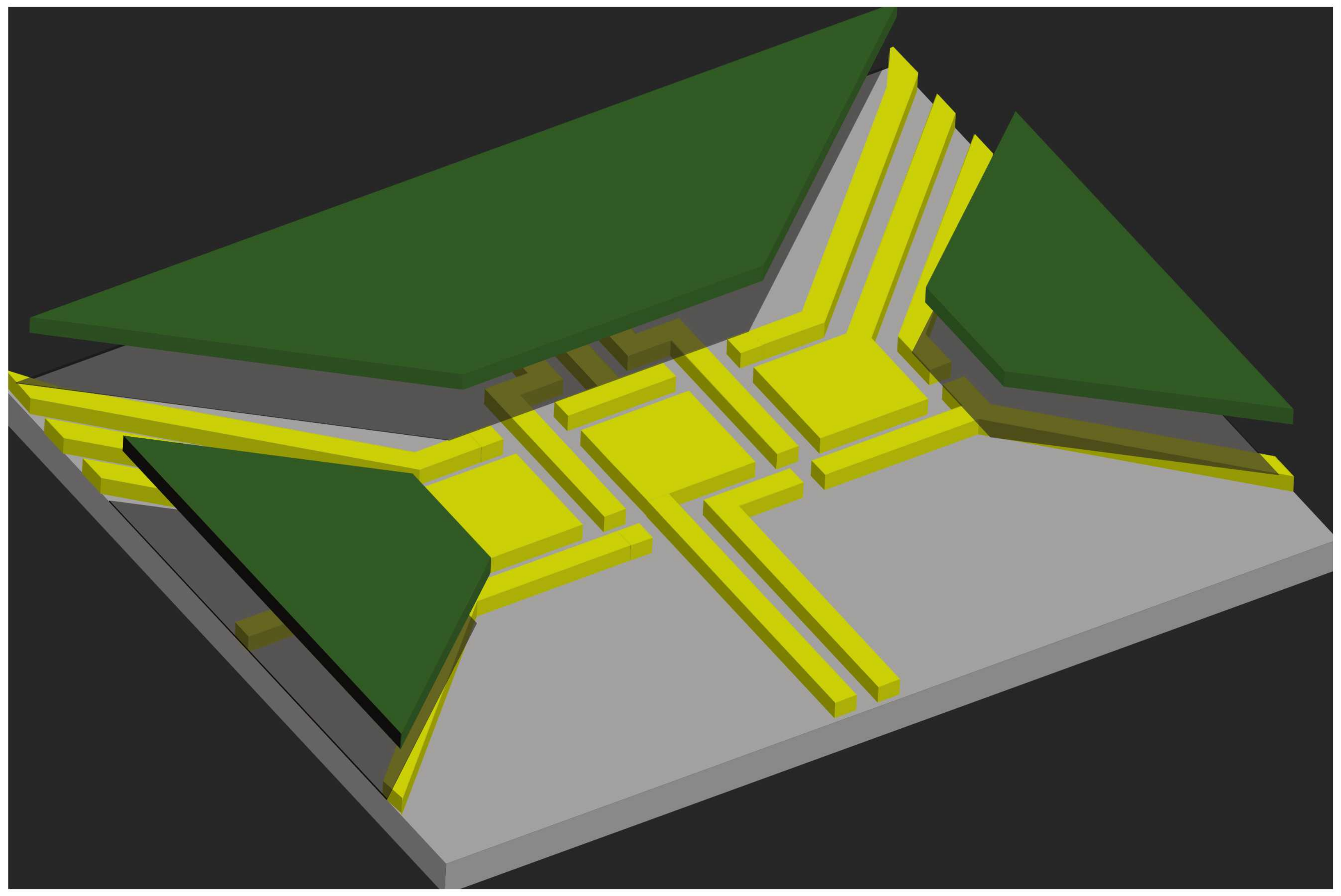
CODA can be applied to finding the optimal size of a device with a given gate design

Test multiple device simulations with the same gate design

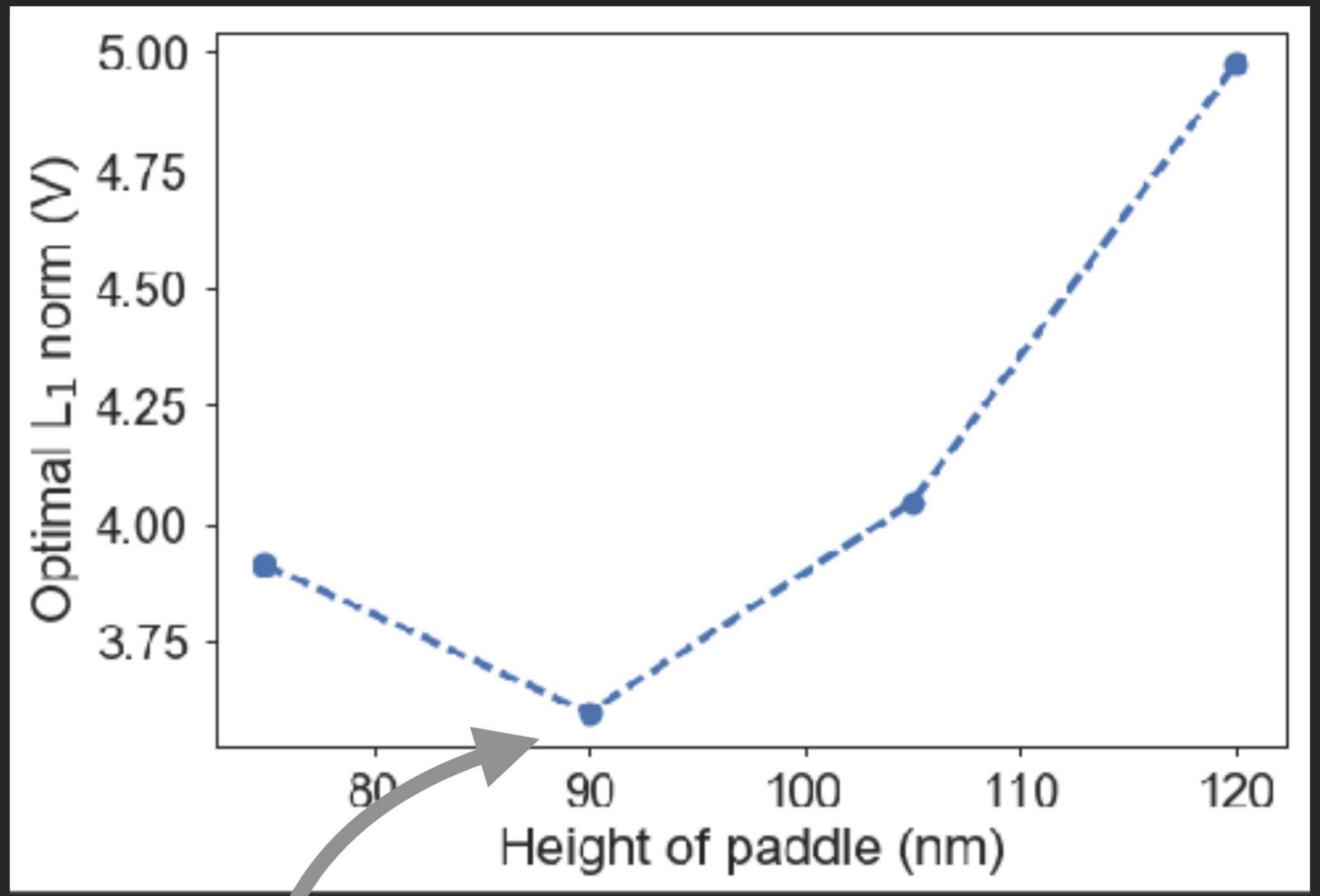
Operational target:

	How we calculate	What we want
Dot occupations	Thomas-Fermi approximation	Reduce from thirty electrons in all three dots to one electron.
Dot energies	Single electron Schrödinger solve	Increase / keep dot energies at 1 meV or above
Tunnel couplings	WKB approximation	Keep tunnel couplings between left / middle dots and middle / right dots constant.

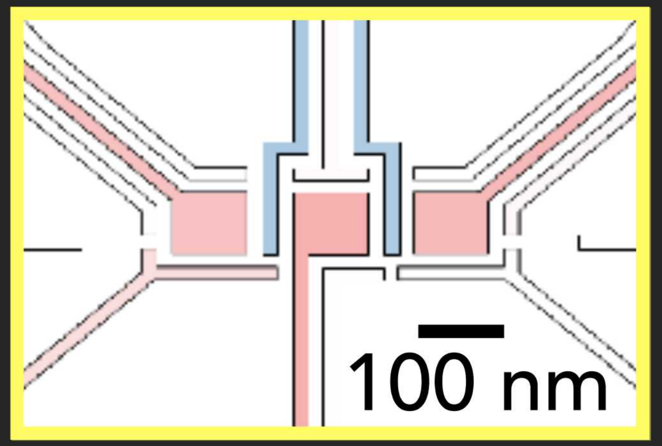


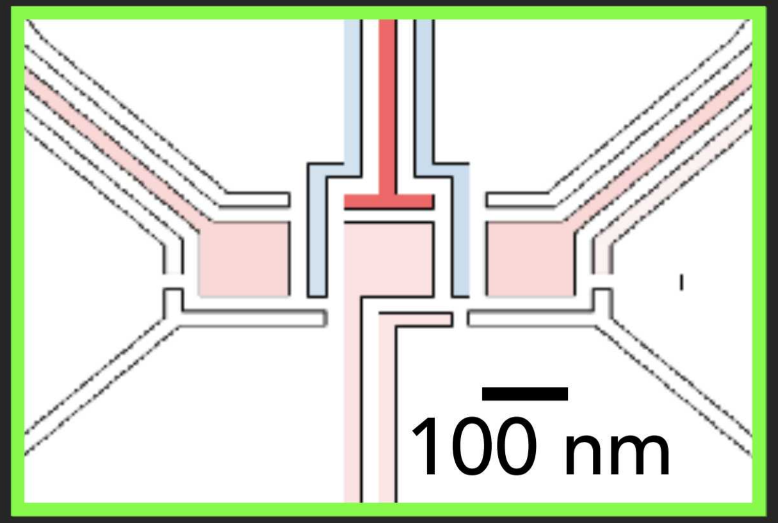


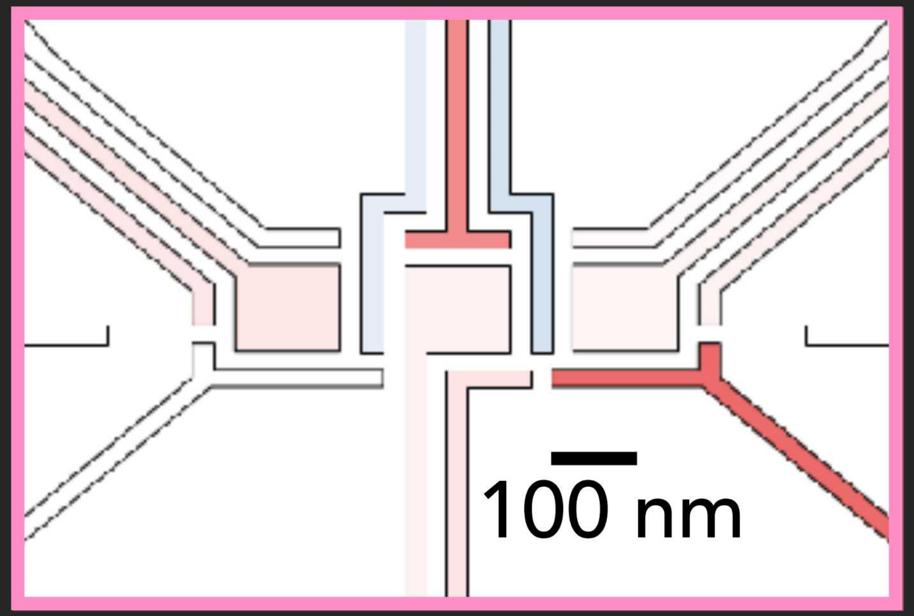
Optimal achievable L_1 norm depends on device size, and has local minimum



Local minimum in device voltage L_1 norm







Smaller devices need larger voltage changes on paddles and direct barrier electrodes

Larger devices need to use more electrodes to control the quantum dots

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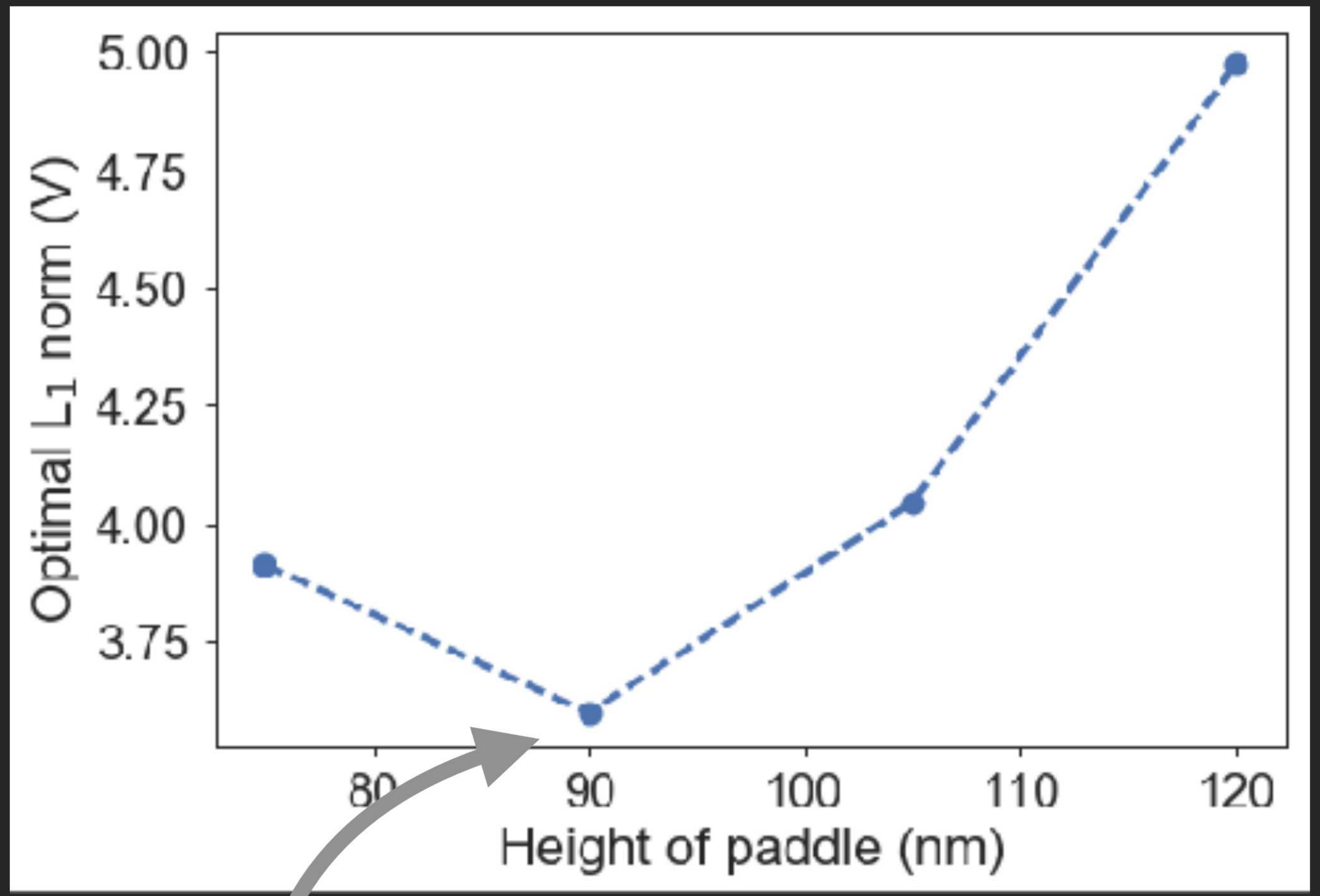

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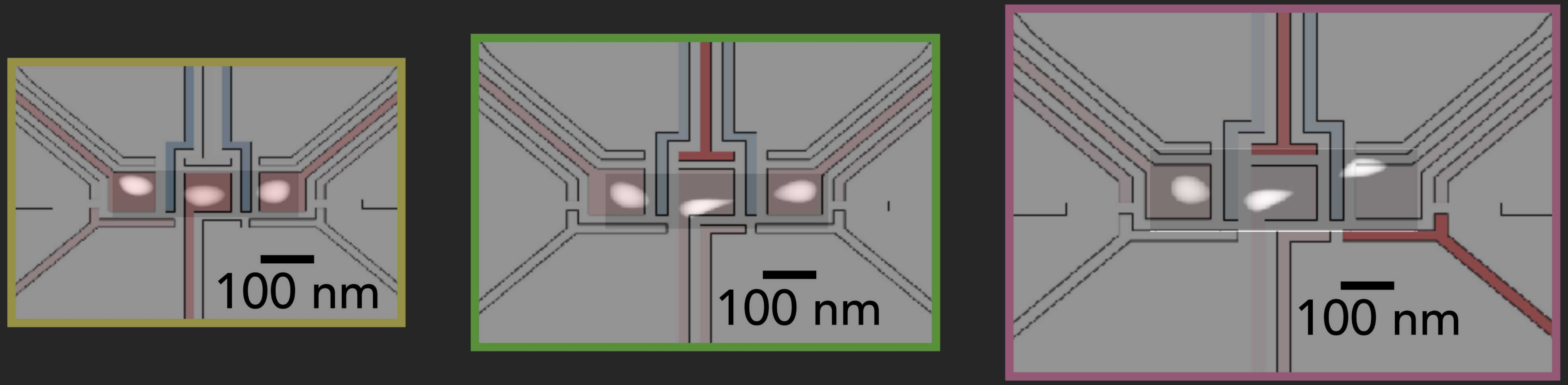

Smaller devices need larger voltage changes on paddles and direct barrier electrodes

Larger devices need to use more electrodes to control the quantum dots

Conclusions

- The CODA procedure can automatically and objectively compare the ”tunability” of different device designs
- It does this by finding the smallest L_1 norm of voltages required to perform a given action on a device
- Using this method we can find the optimal size of a device

Thank you!

Additional Slides