Differentiable Ray Tracing for Telecommunications

Jérome Eertmans - July 17th, Siegen

About the author

About the author

Profile:

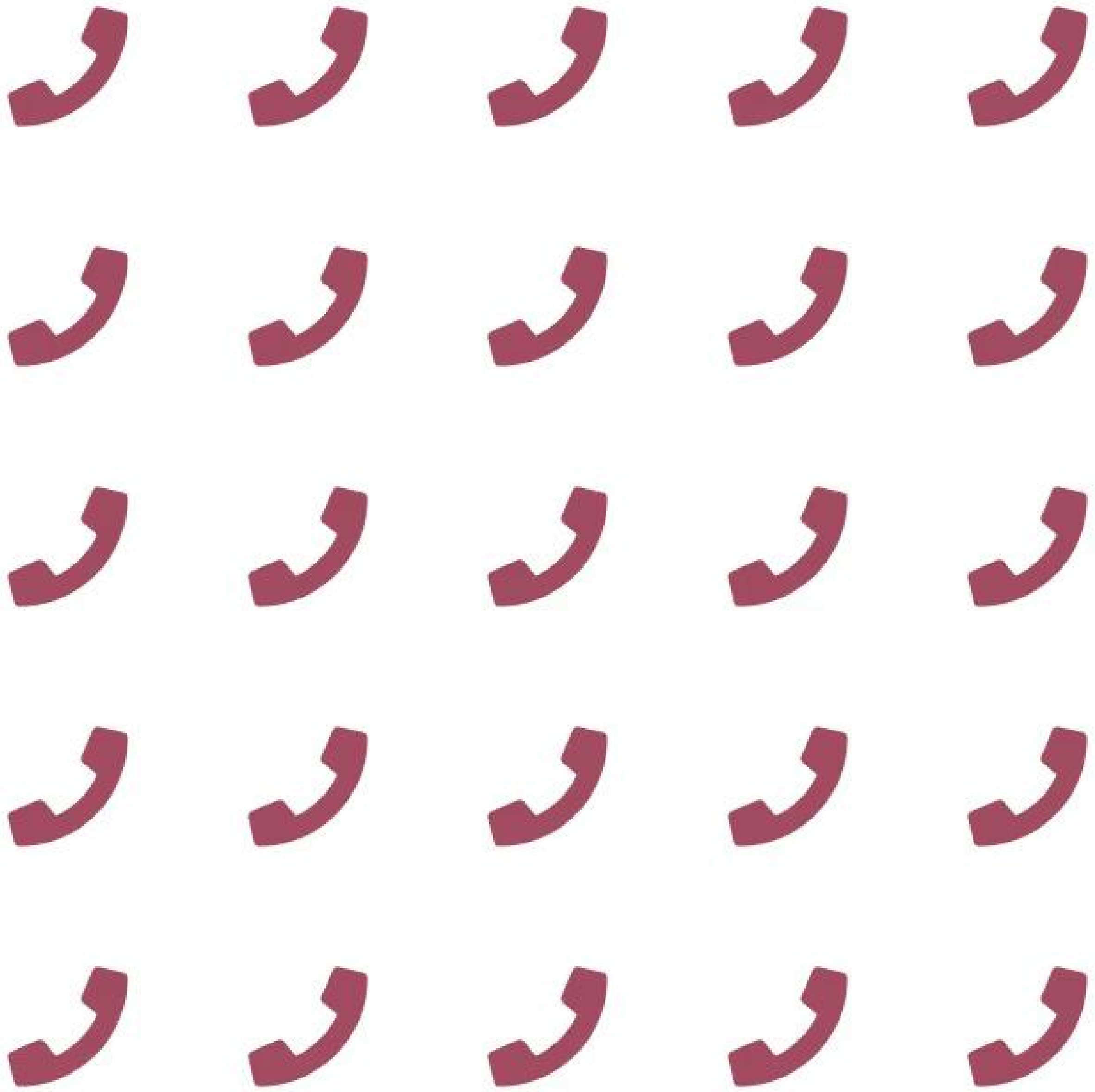
- PhD student at UCLouvain since 09/2021;
- Electromechaninal Engineer in mechatronics;
- introduced to Ray Tracing (RT) during a student job.

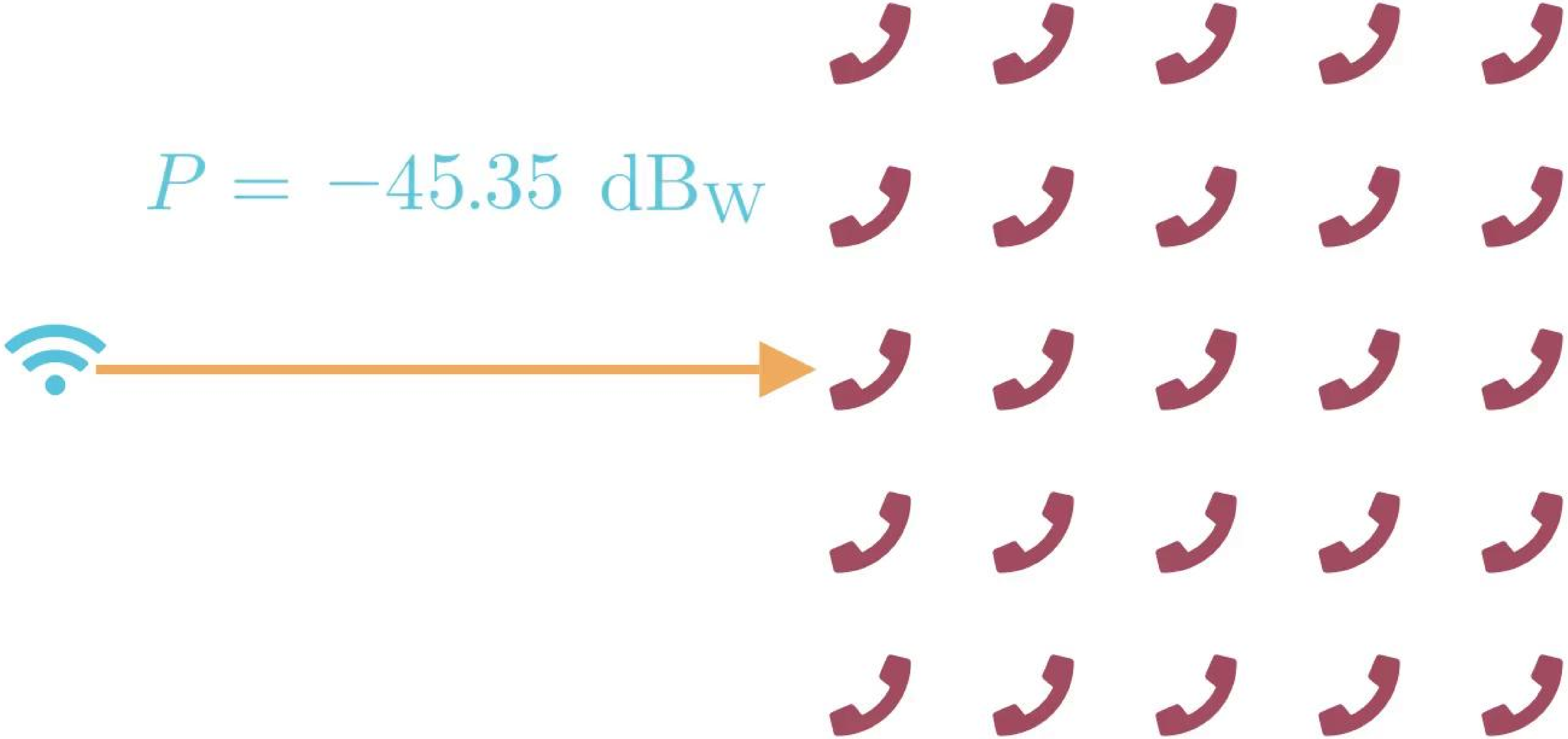
Interests:

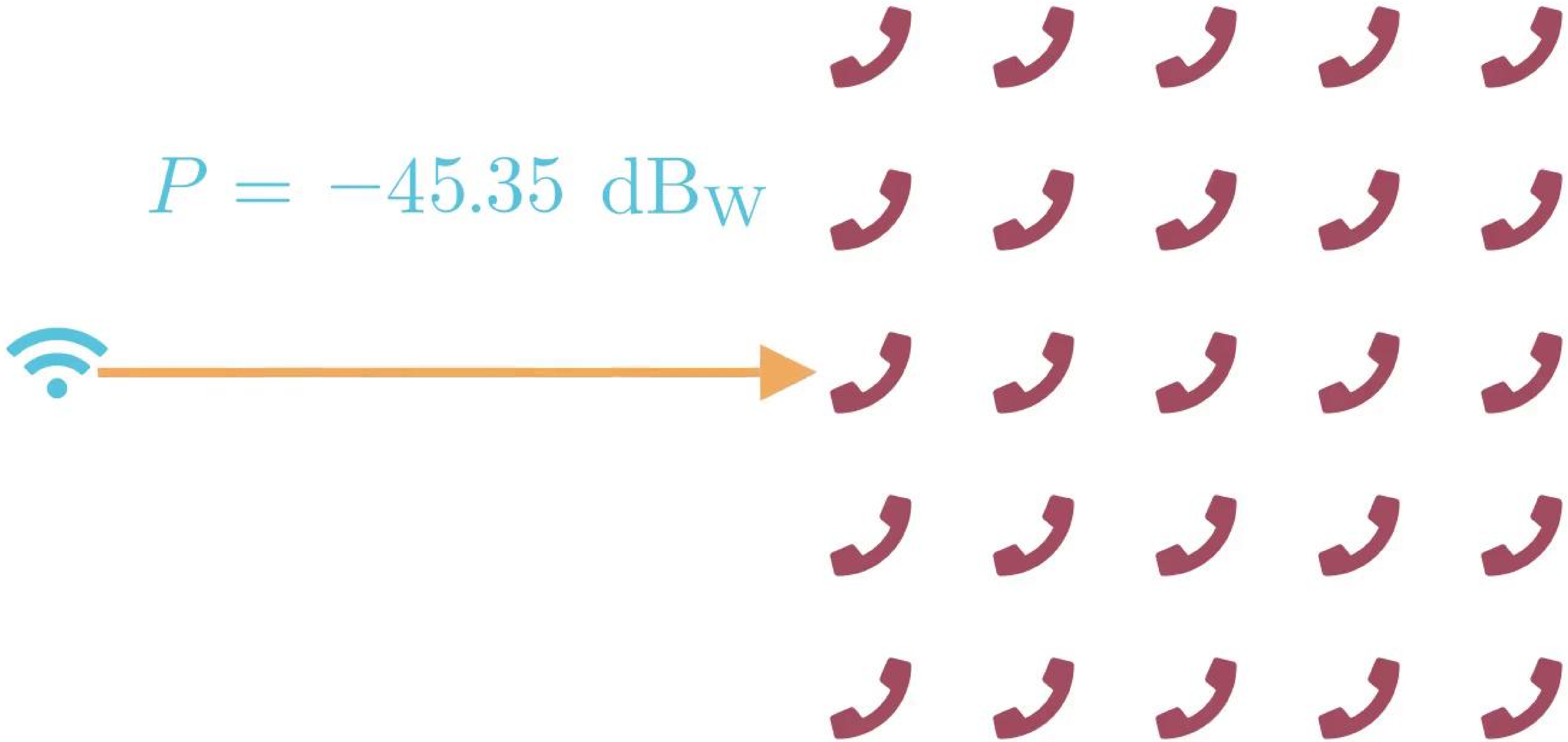
- Programming;
- Writing performant solutions;
- and open sourcing content (jeertmans on or eertmans.be).

Claude Oestges

Laurent Jacques




$P = -45.35\ \mathrm{dB_W}$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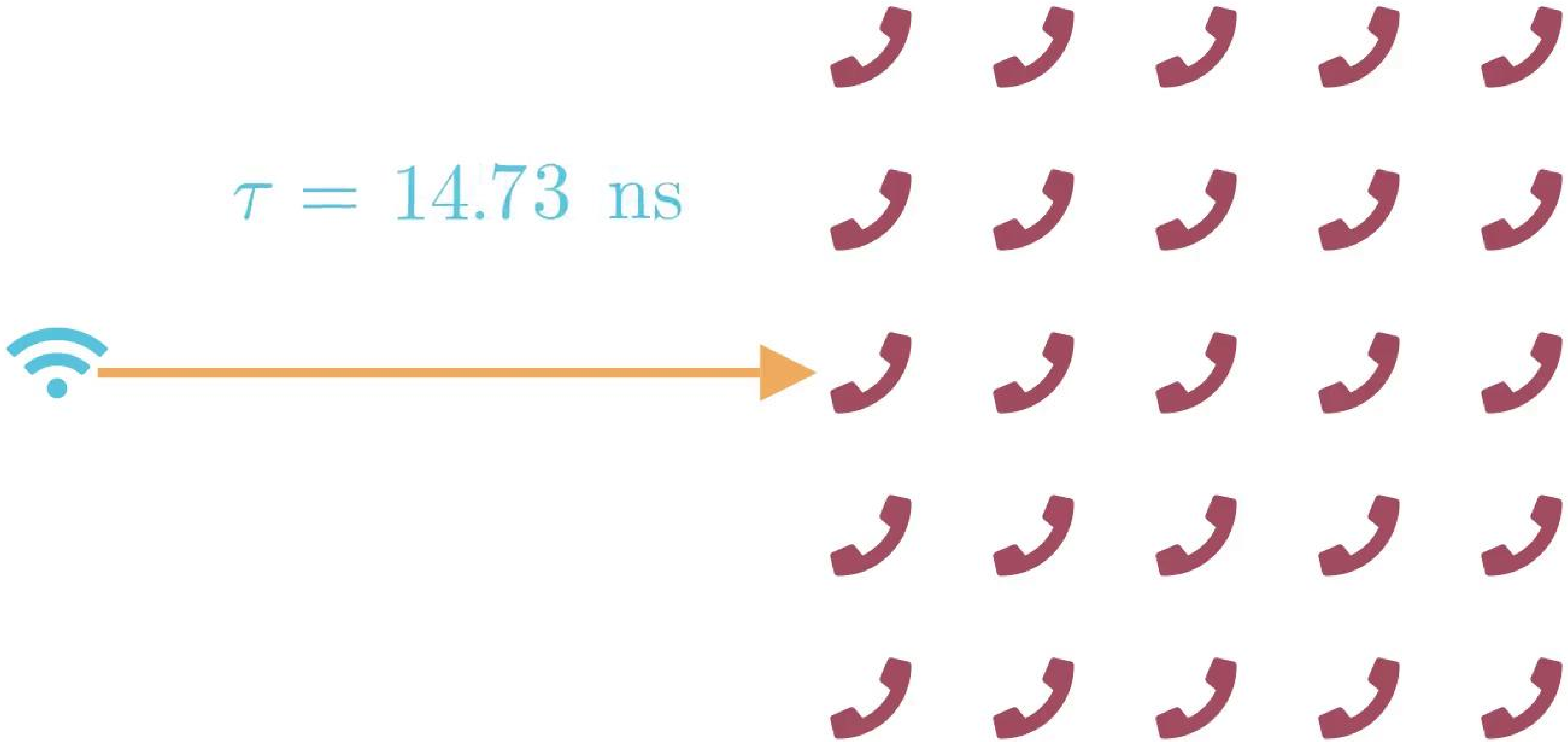
$\tau = 14.73$ ns


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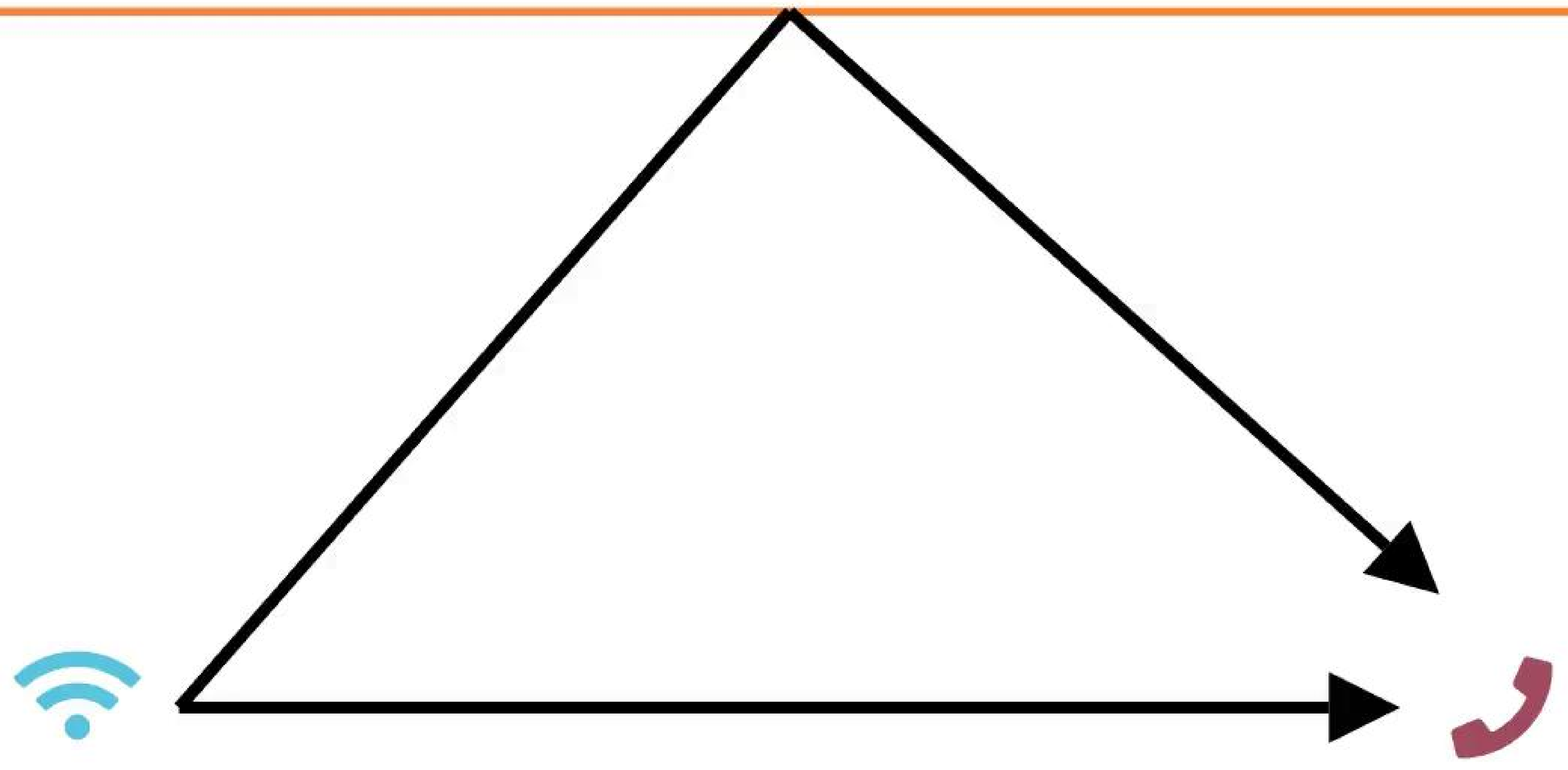

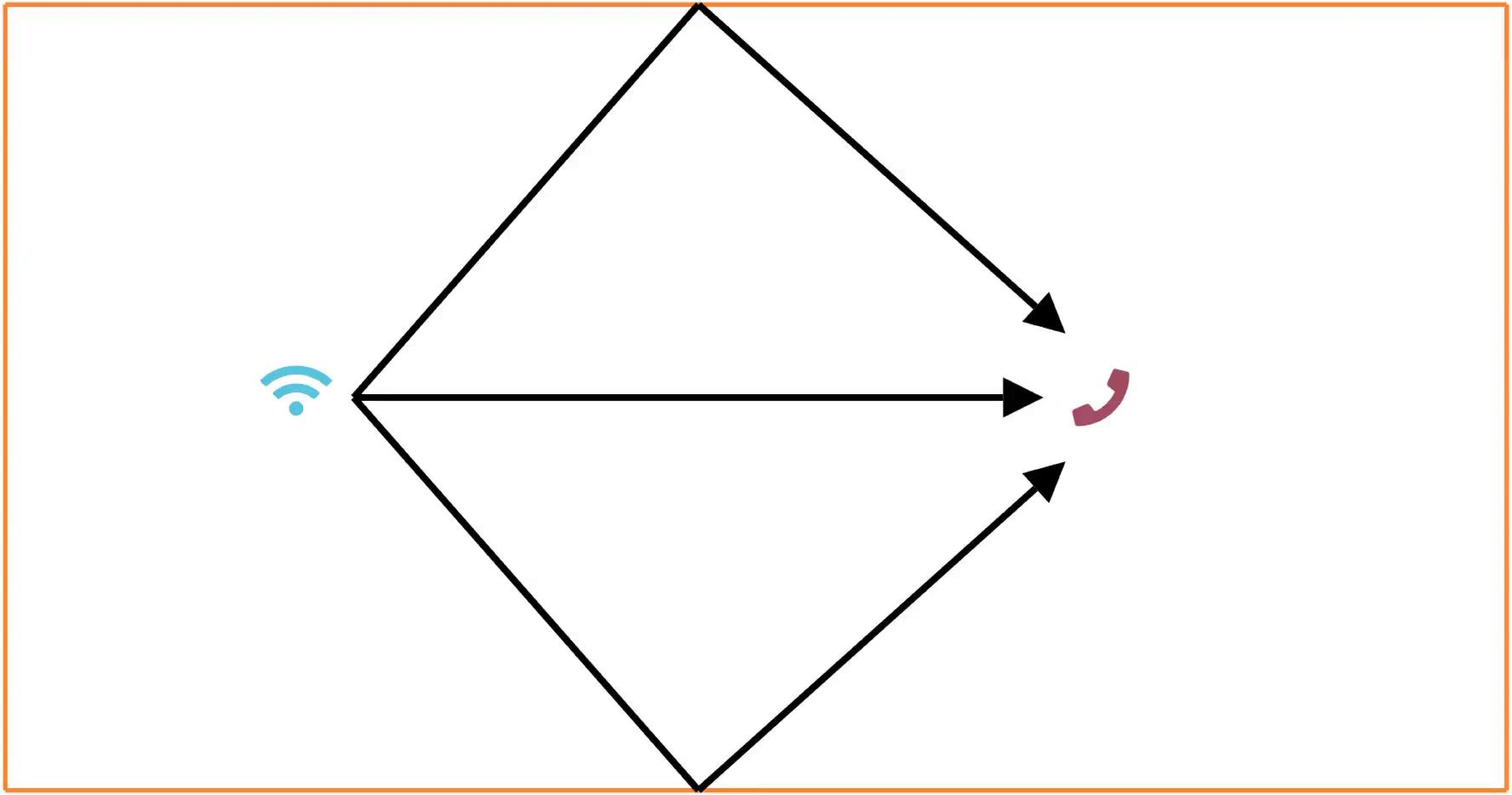

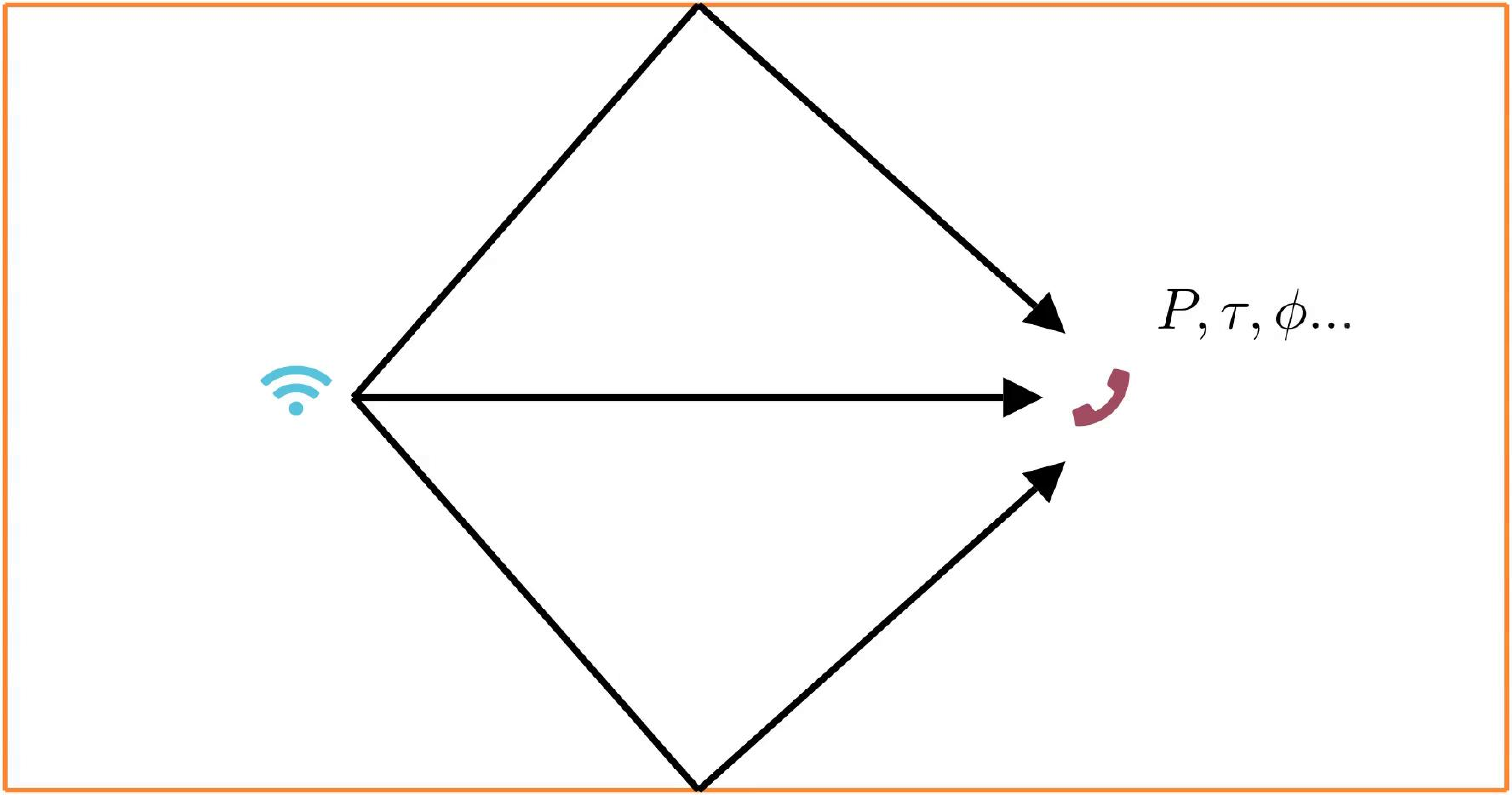
$P, \tau, \phi ...$

How to find all paths?

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Multiple methods exist!

Outline:

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1. RT for Telecom

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2. Image Method

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3. Min-Path-Tracing

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4. About differentiability

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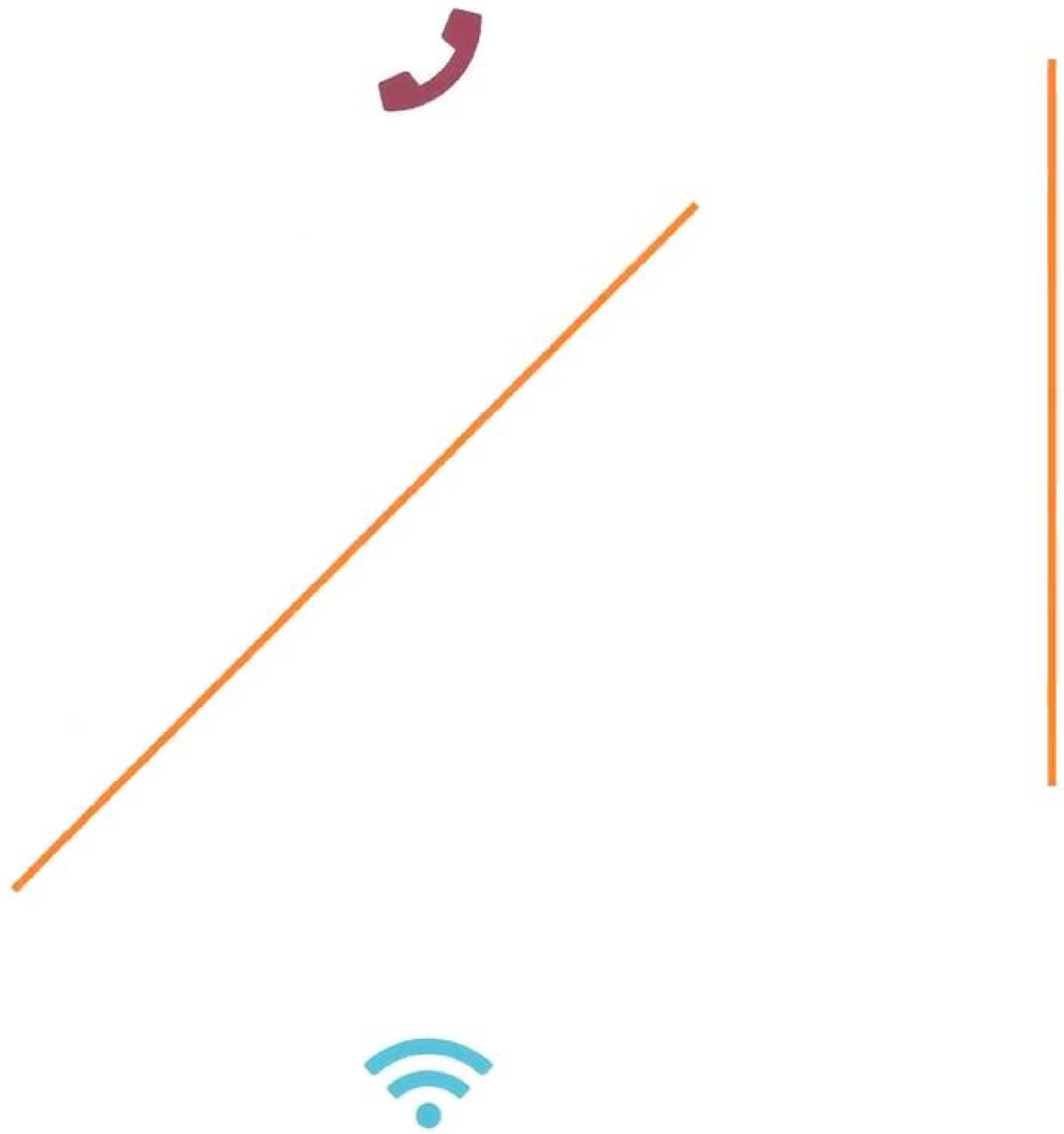
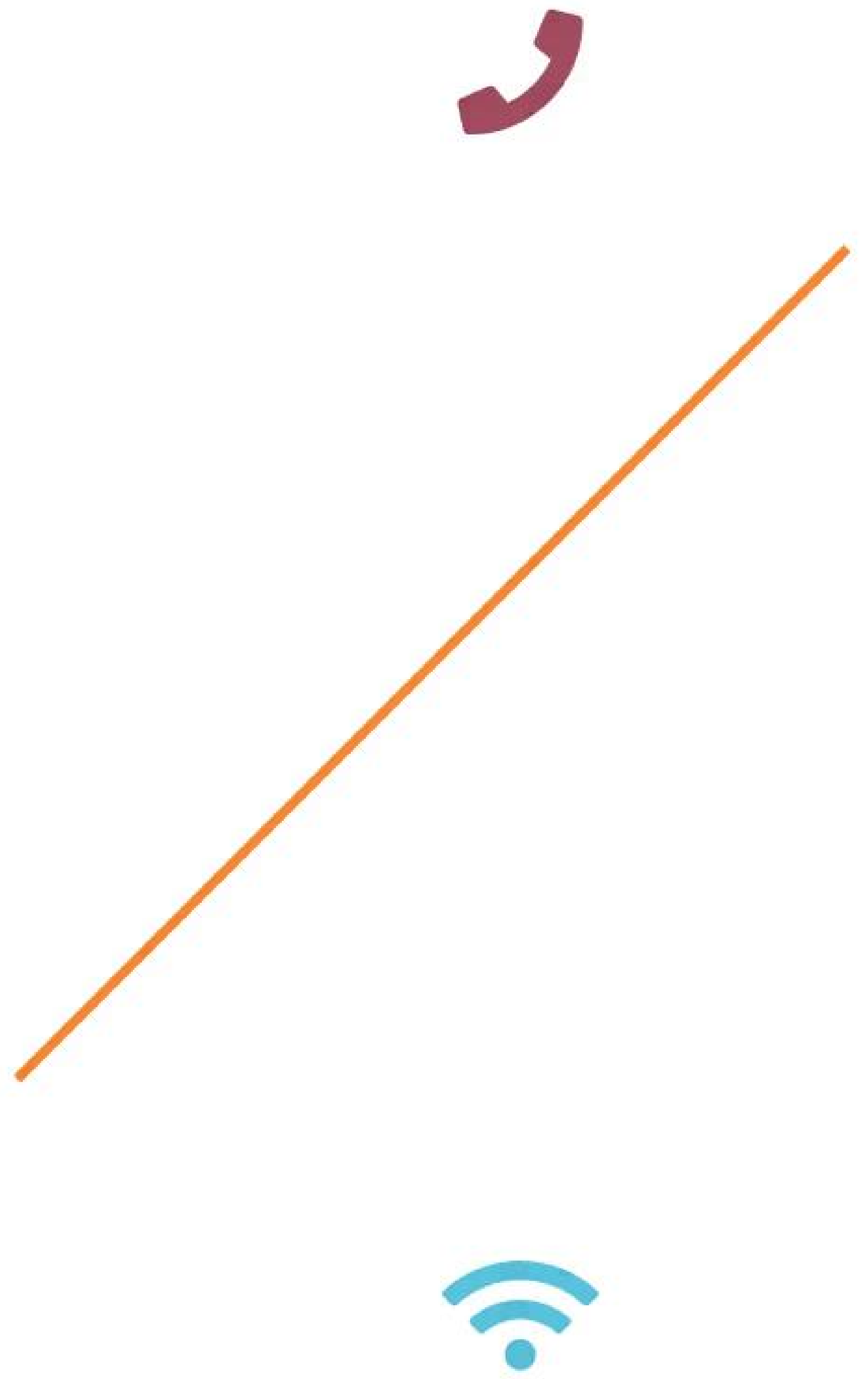
5. Current work

1. RT for Telecom



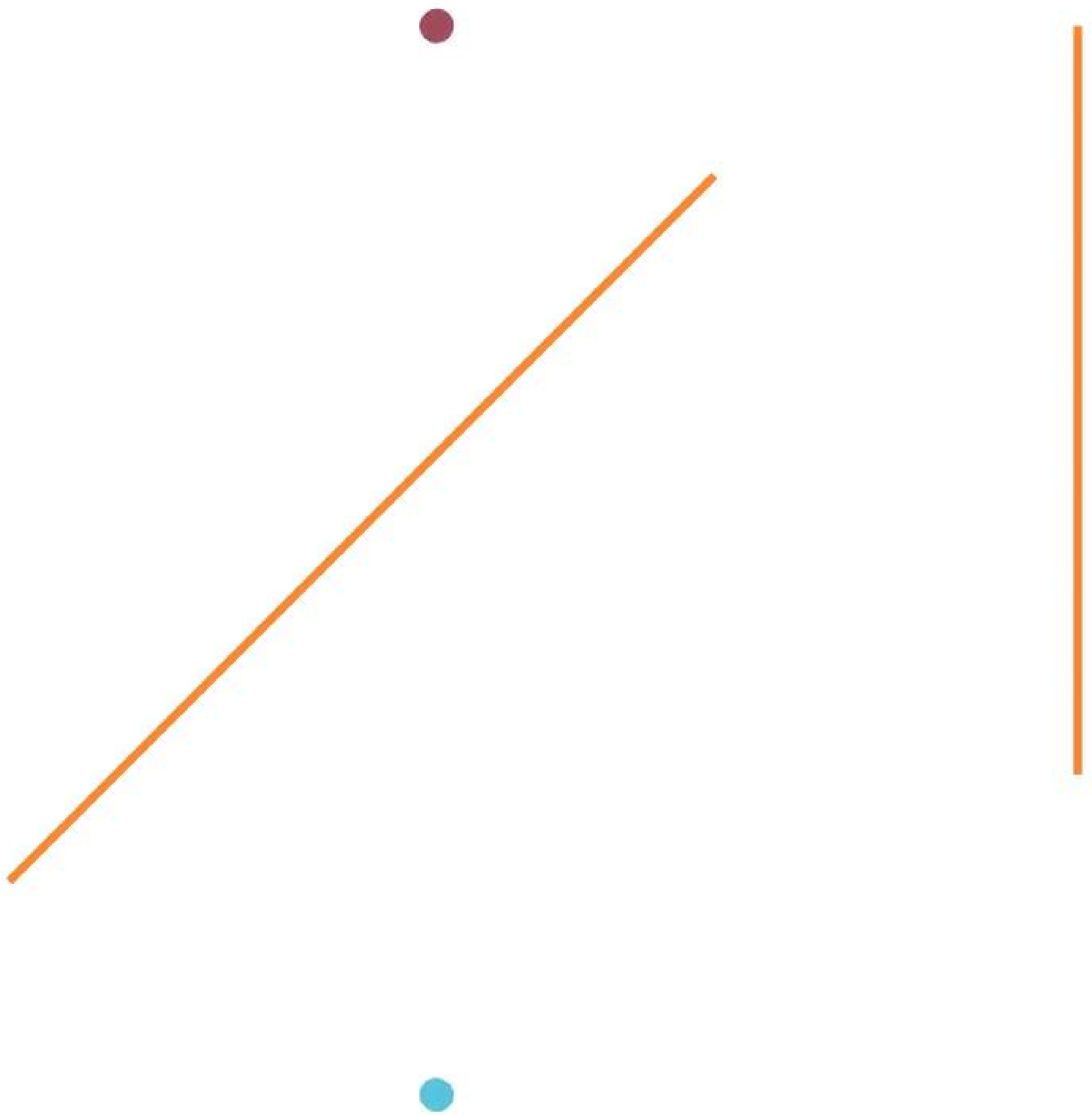
1. RT for Telecom



Core points:

- used by telecom operators;
- for coverage map;
- for antennas placement;
- using mix of Ray-Launching and Image RT.

2. Image Method



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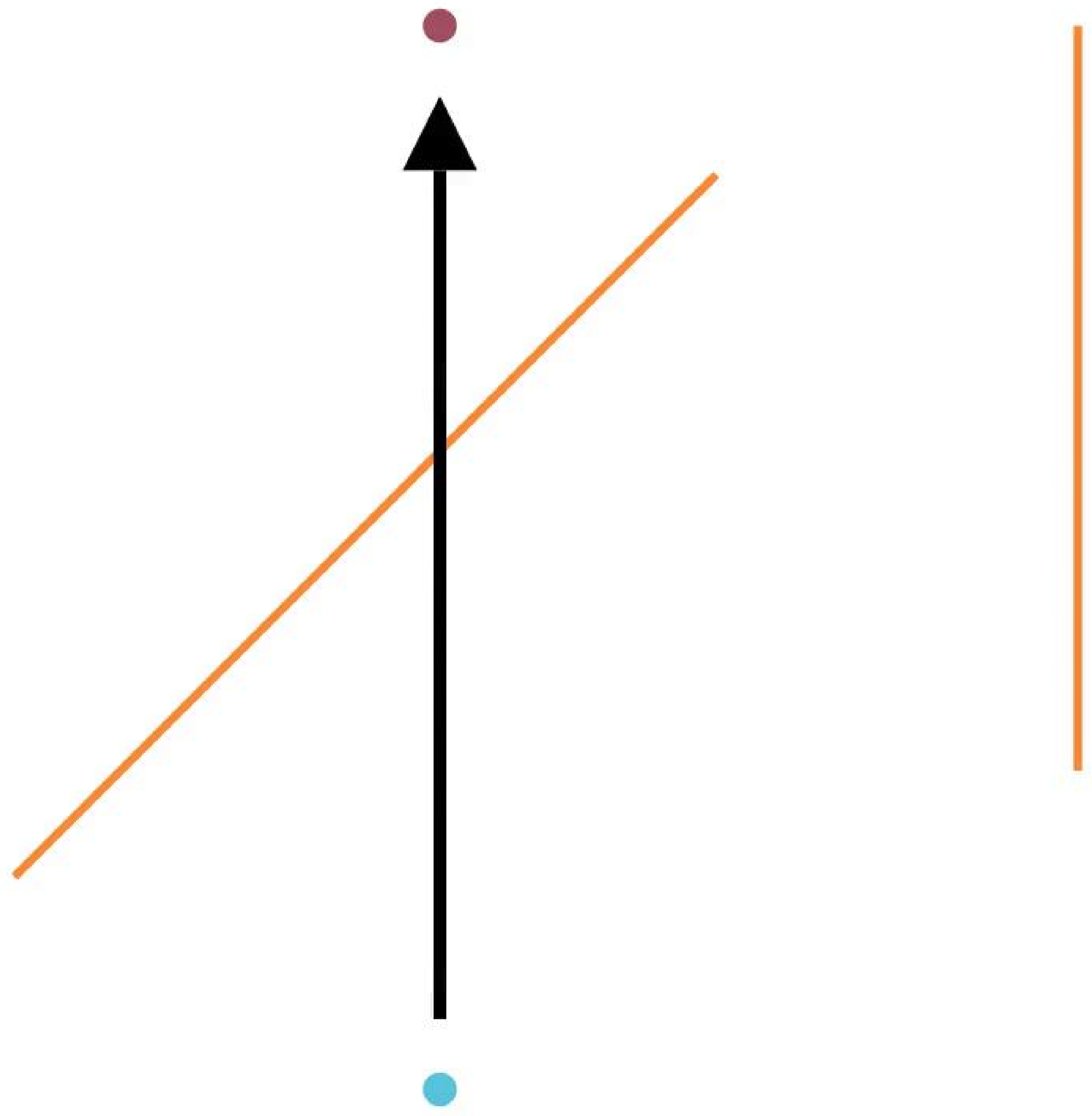

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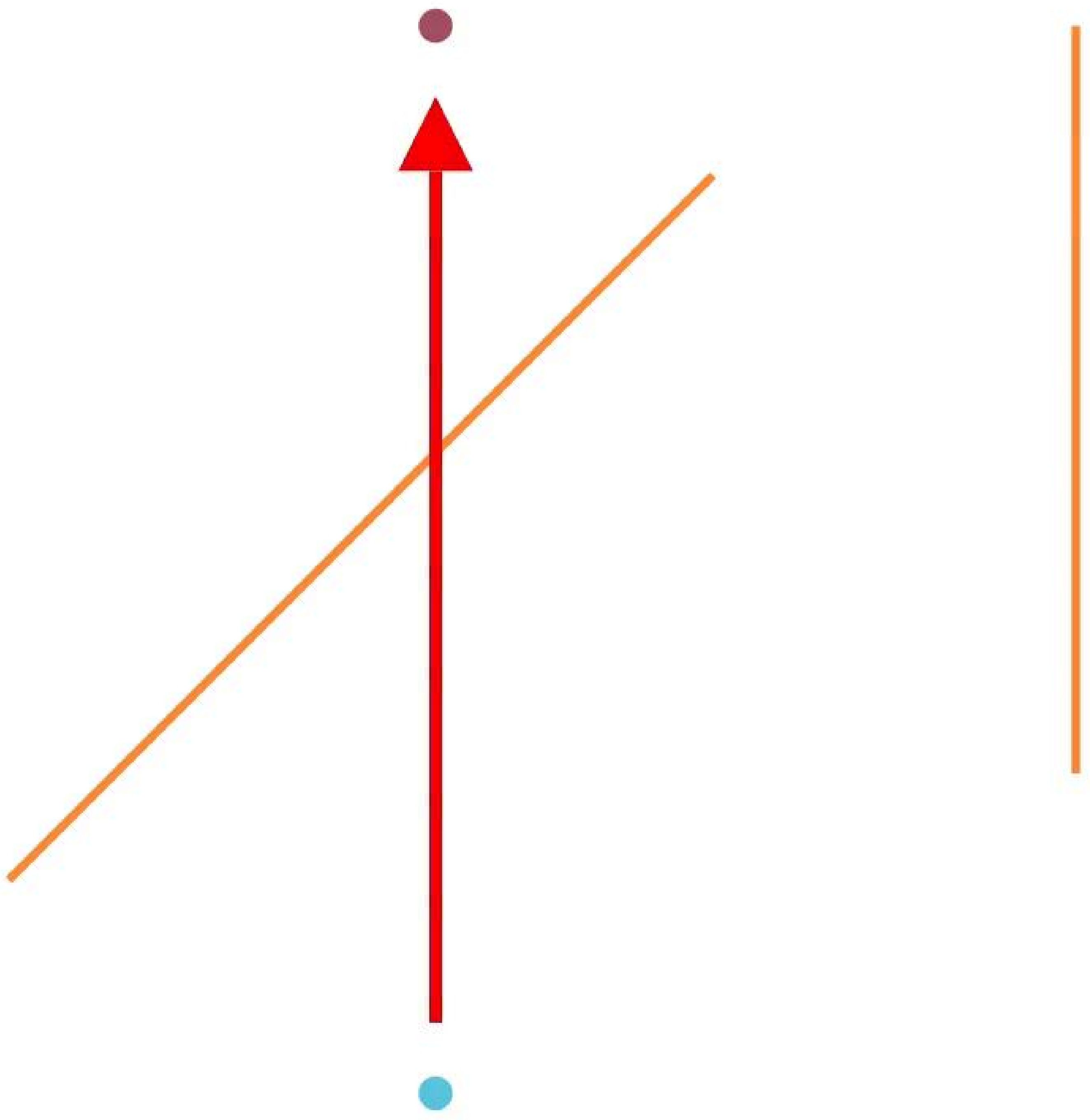

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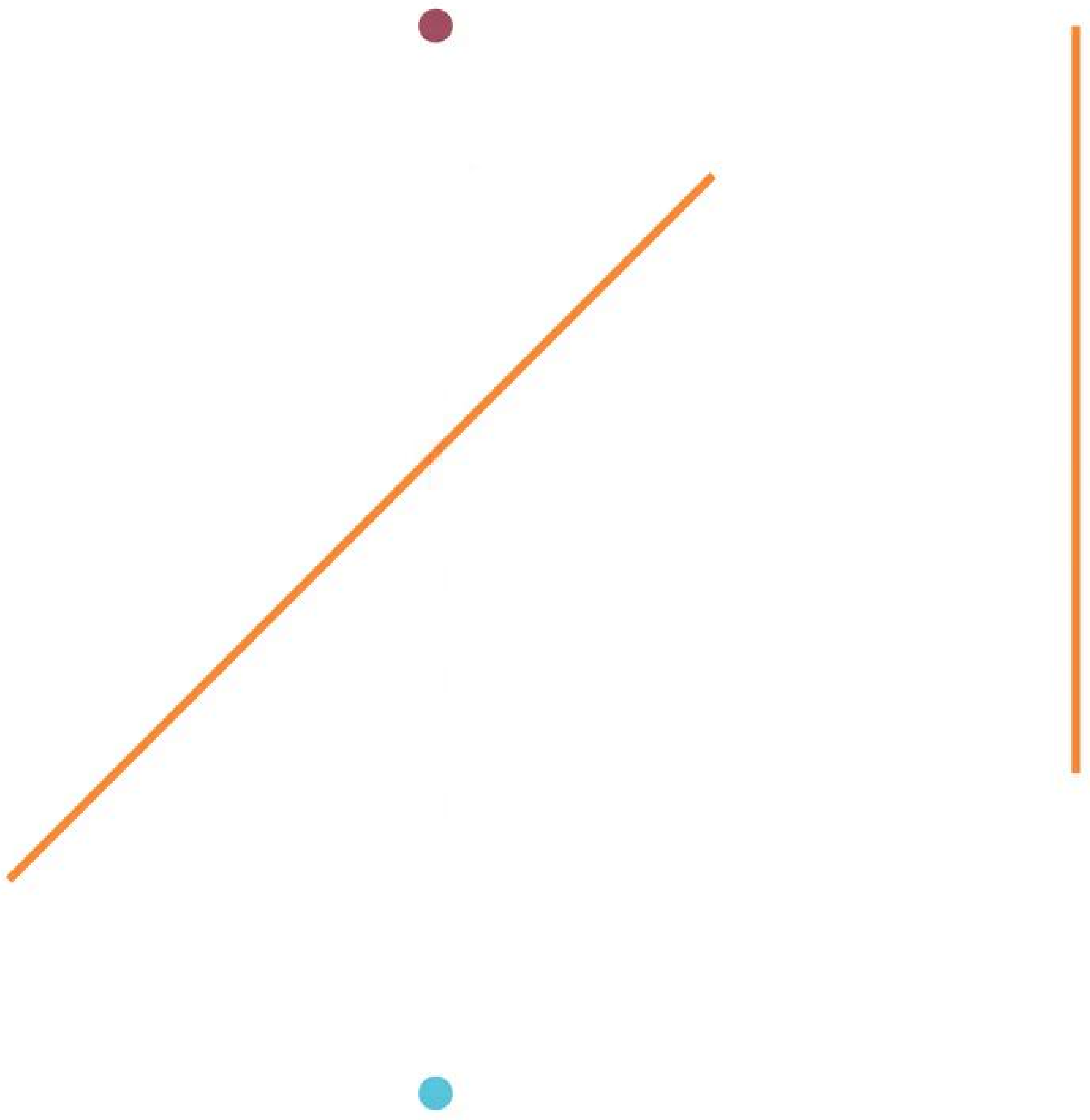

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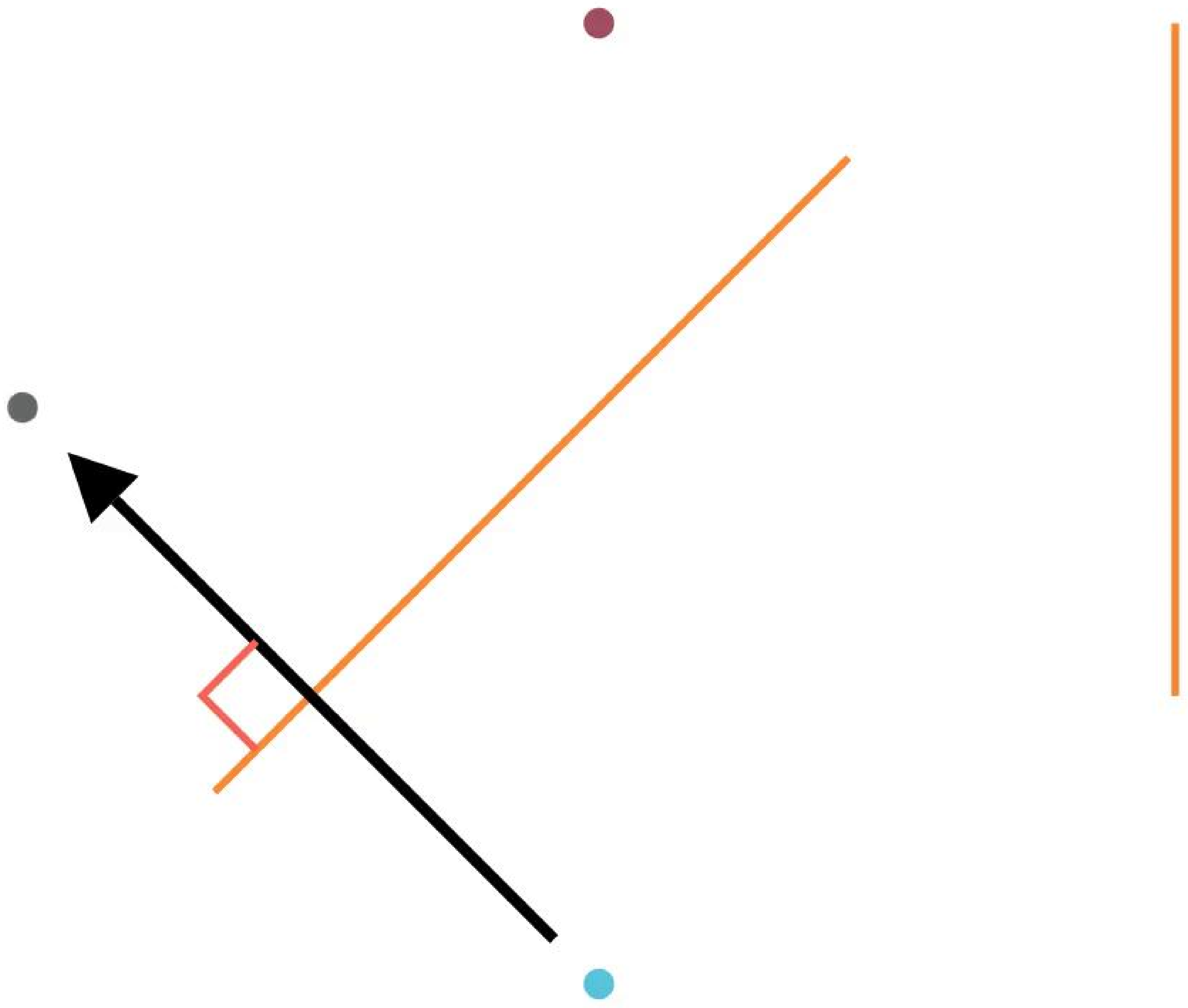

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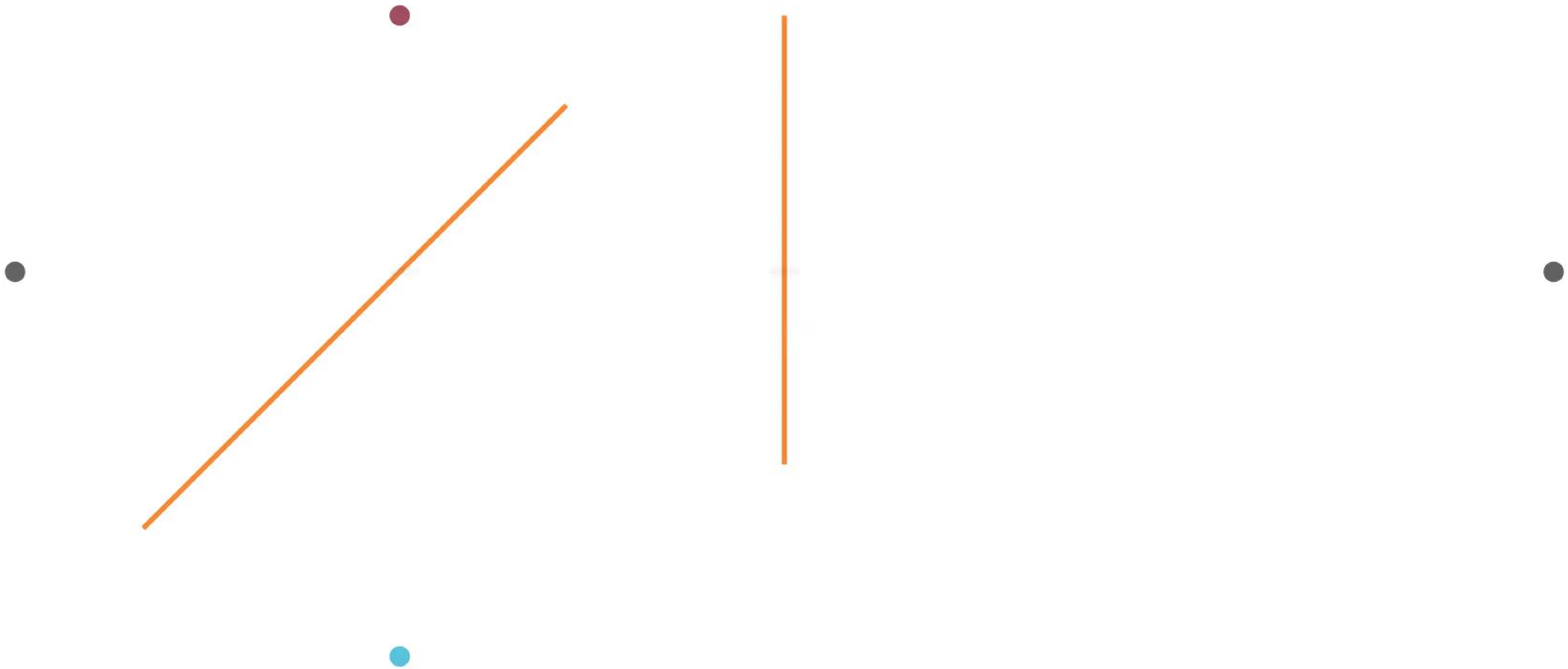

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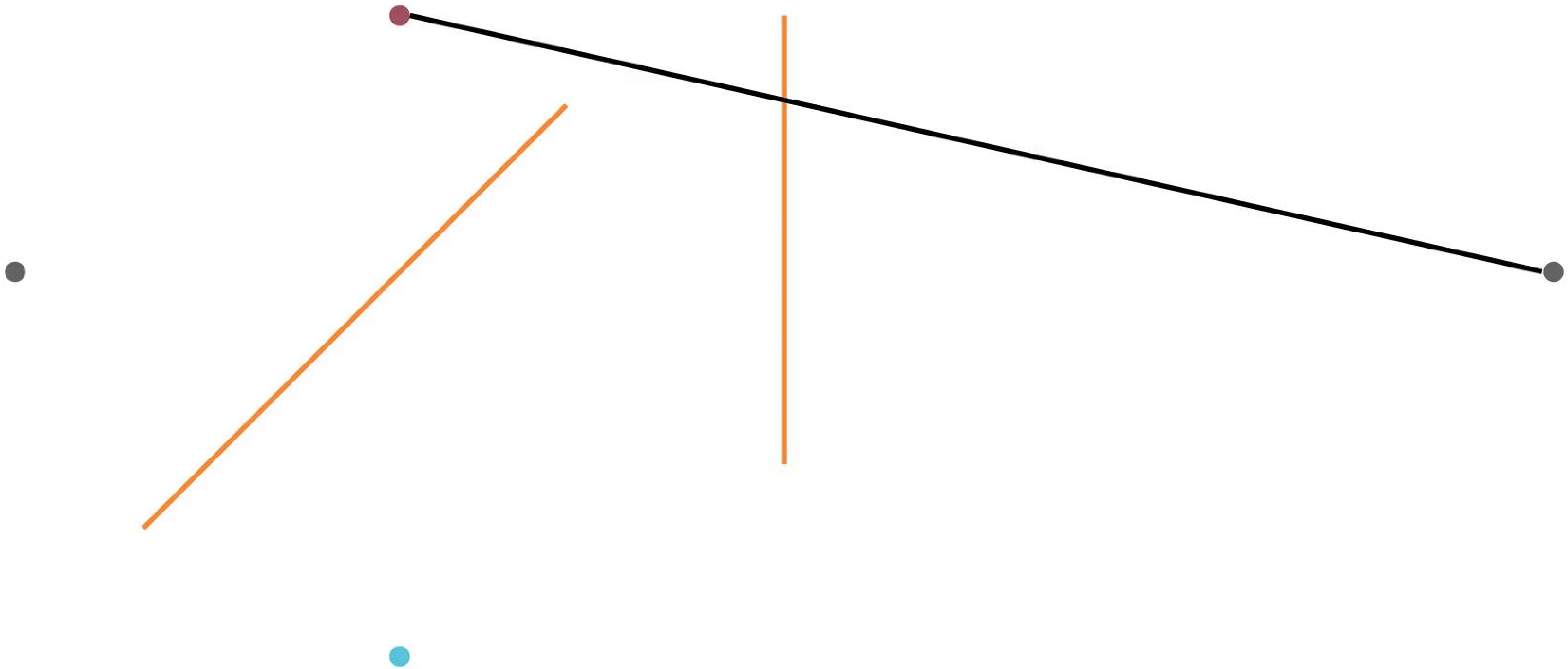

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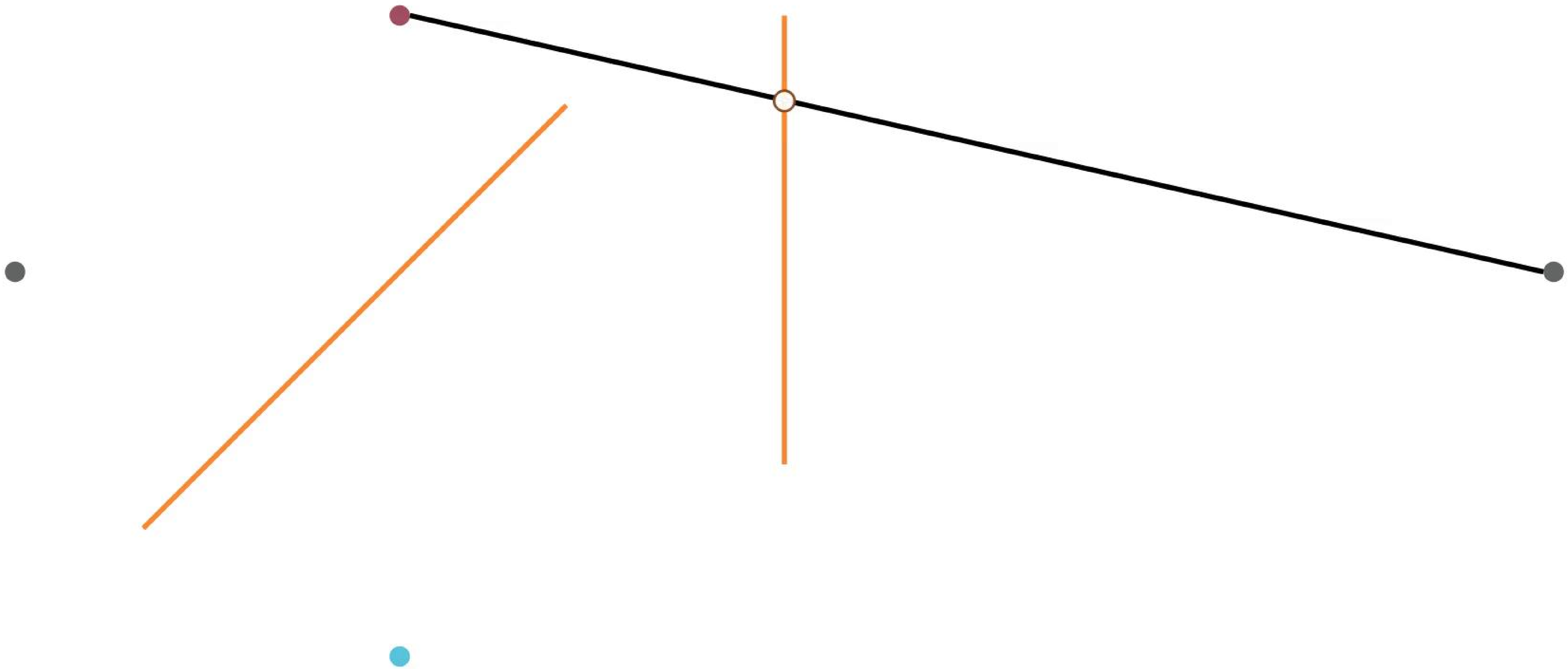

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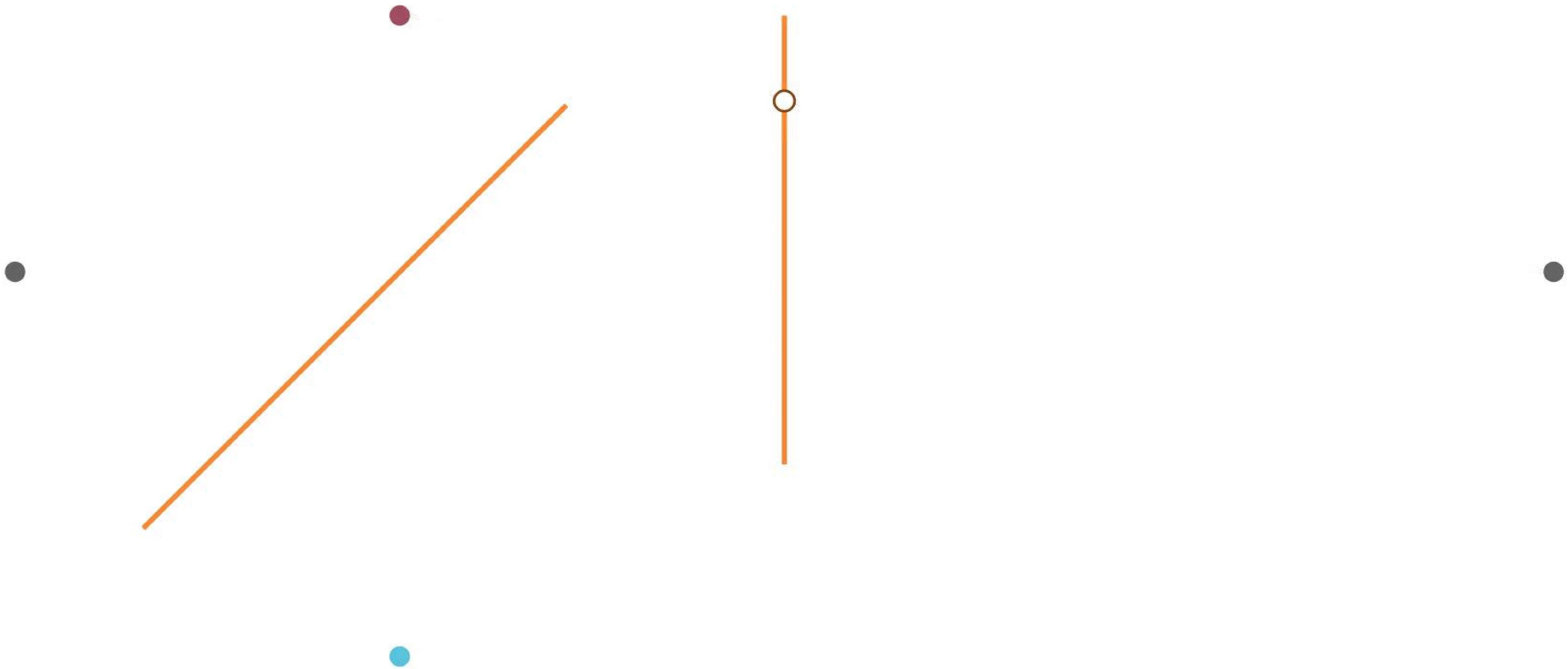

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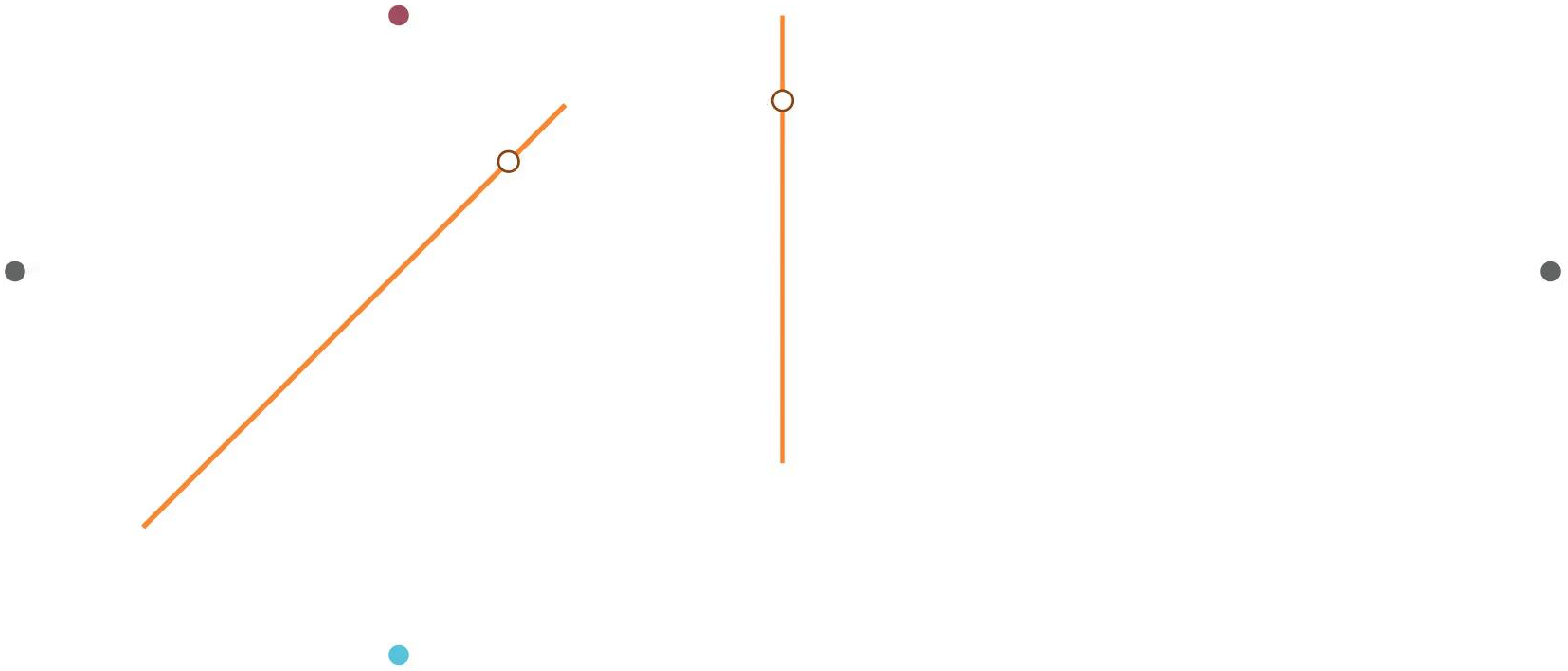

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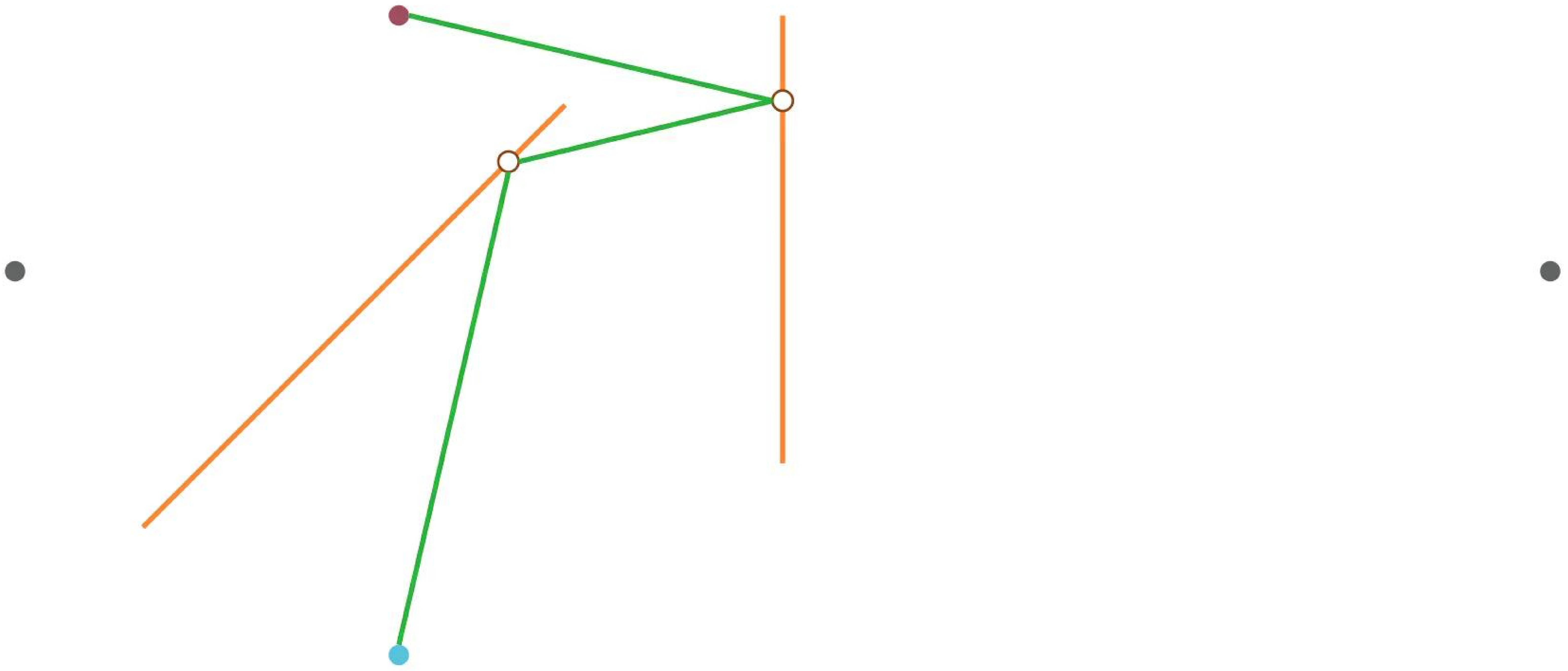

Summary:

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Pros

- Simple
- Fast - $\mathcal{O}(n)$

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Pros

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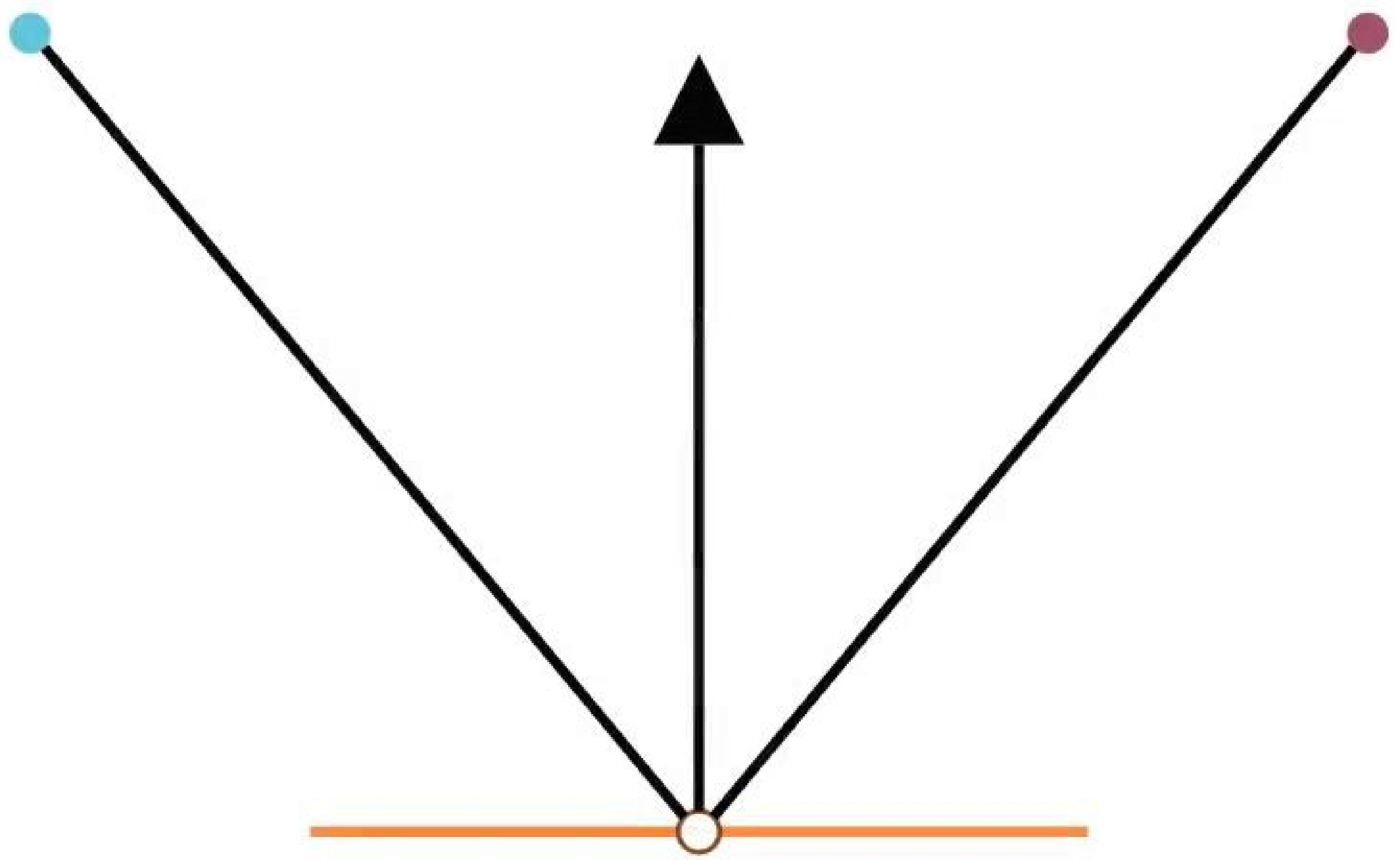
Cons

- Limited to planar surfaces
- Specular reflection only

3. Min-Path-Tracing



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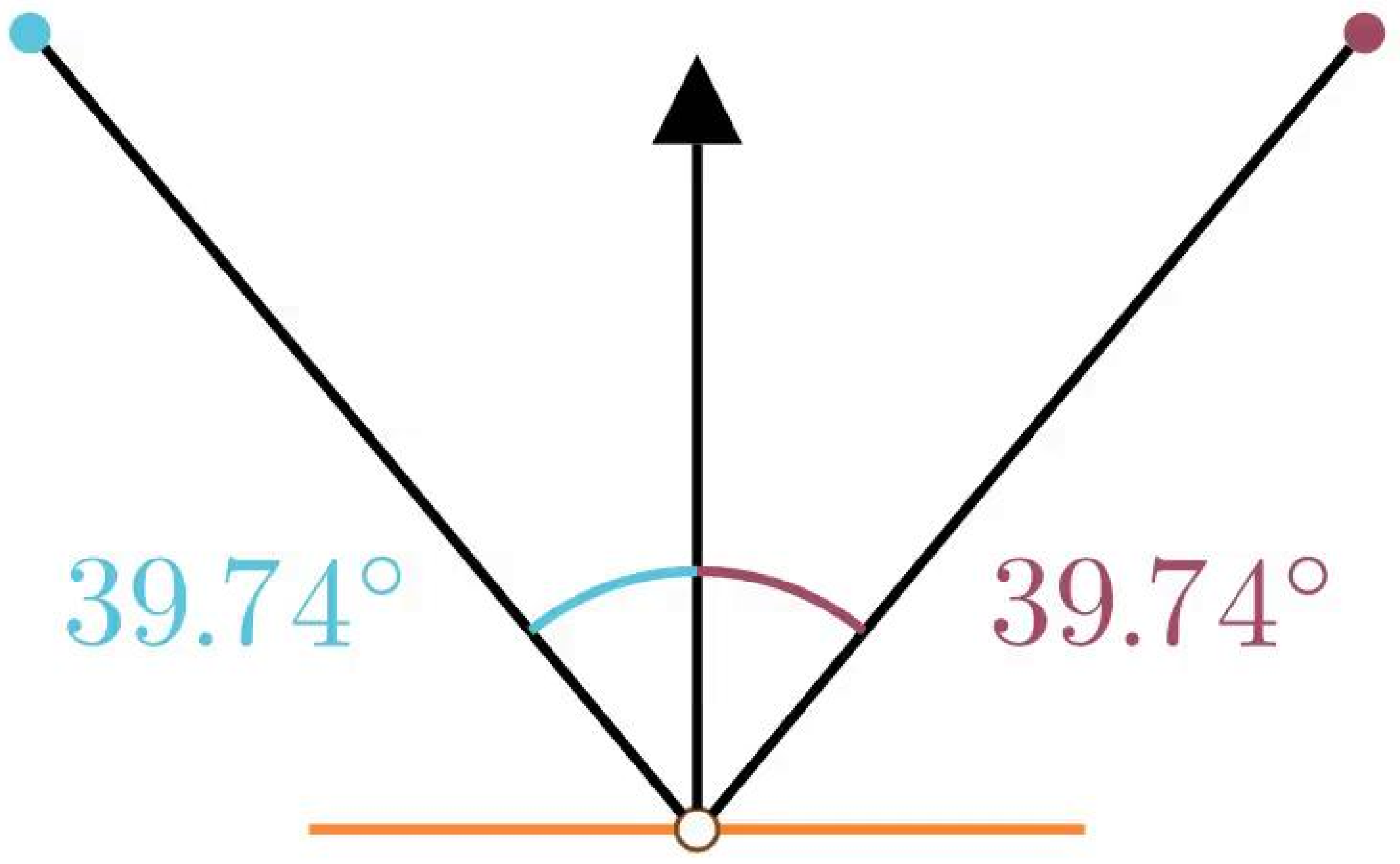

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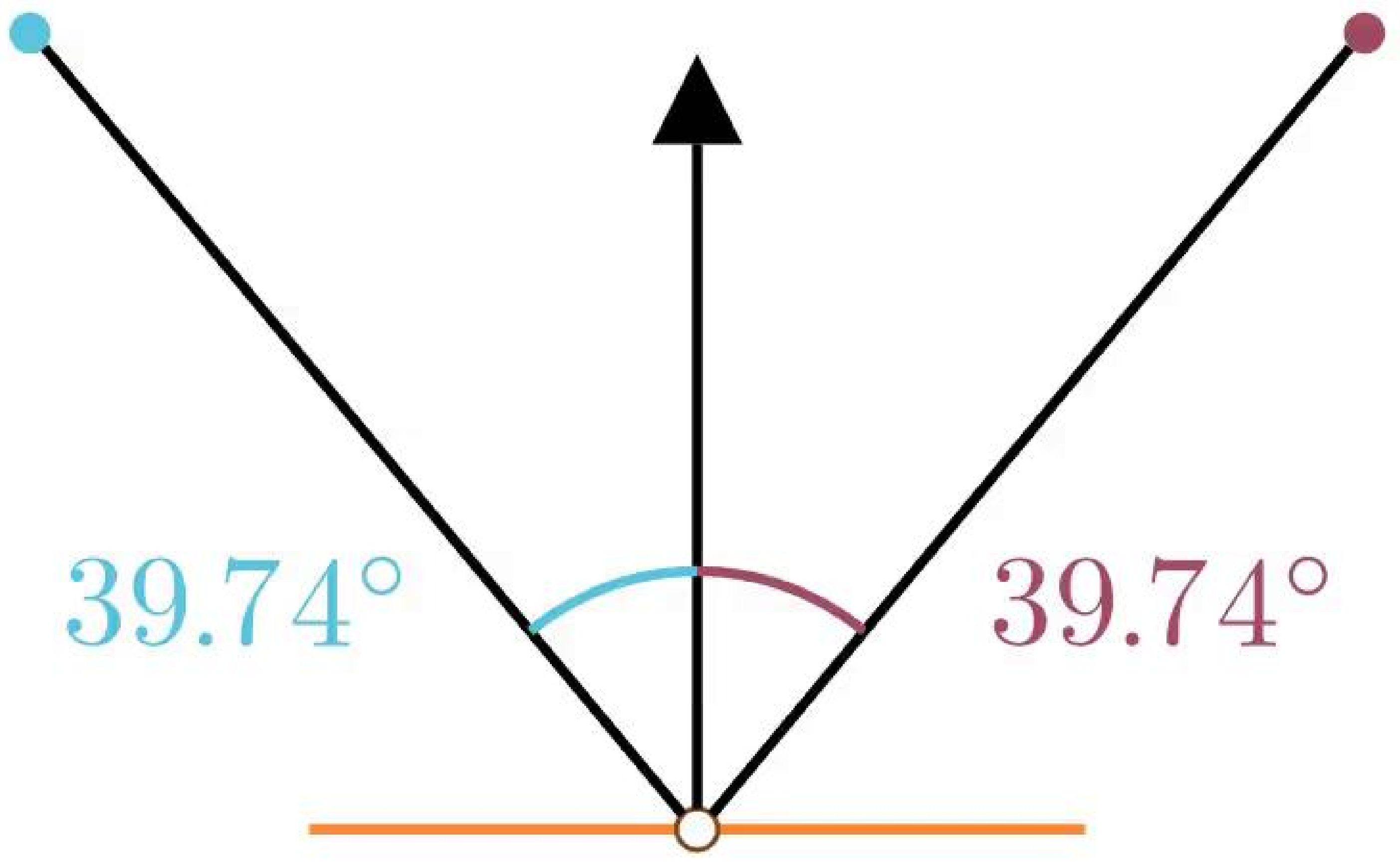

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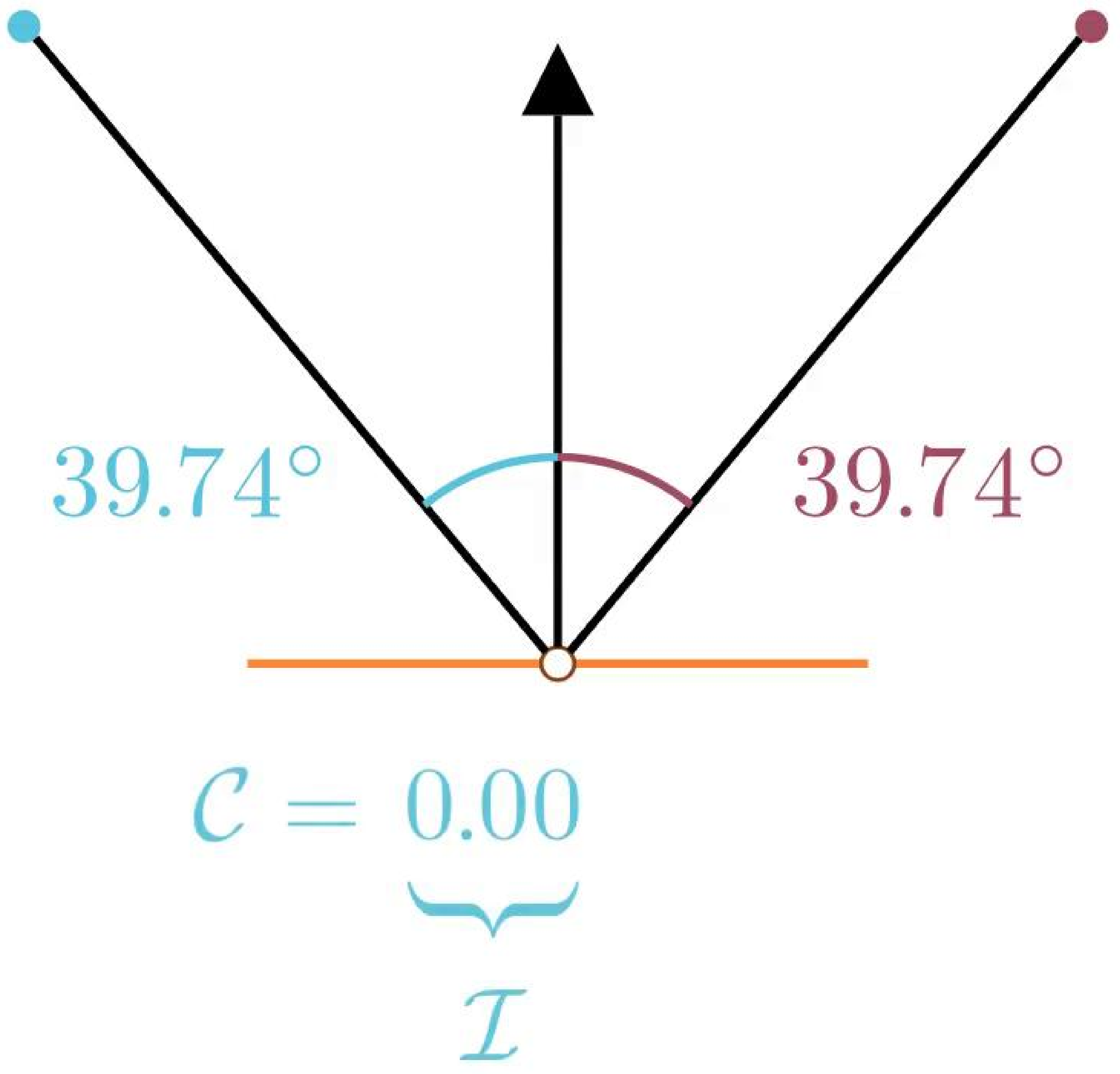

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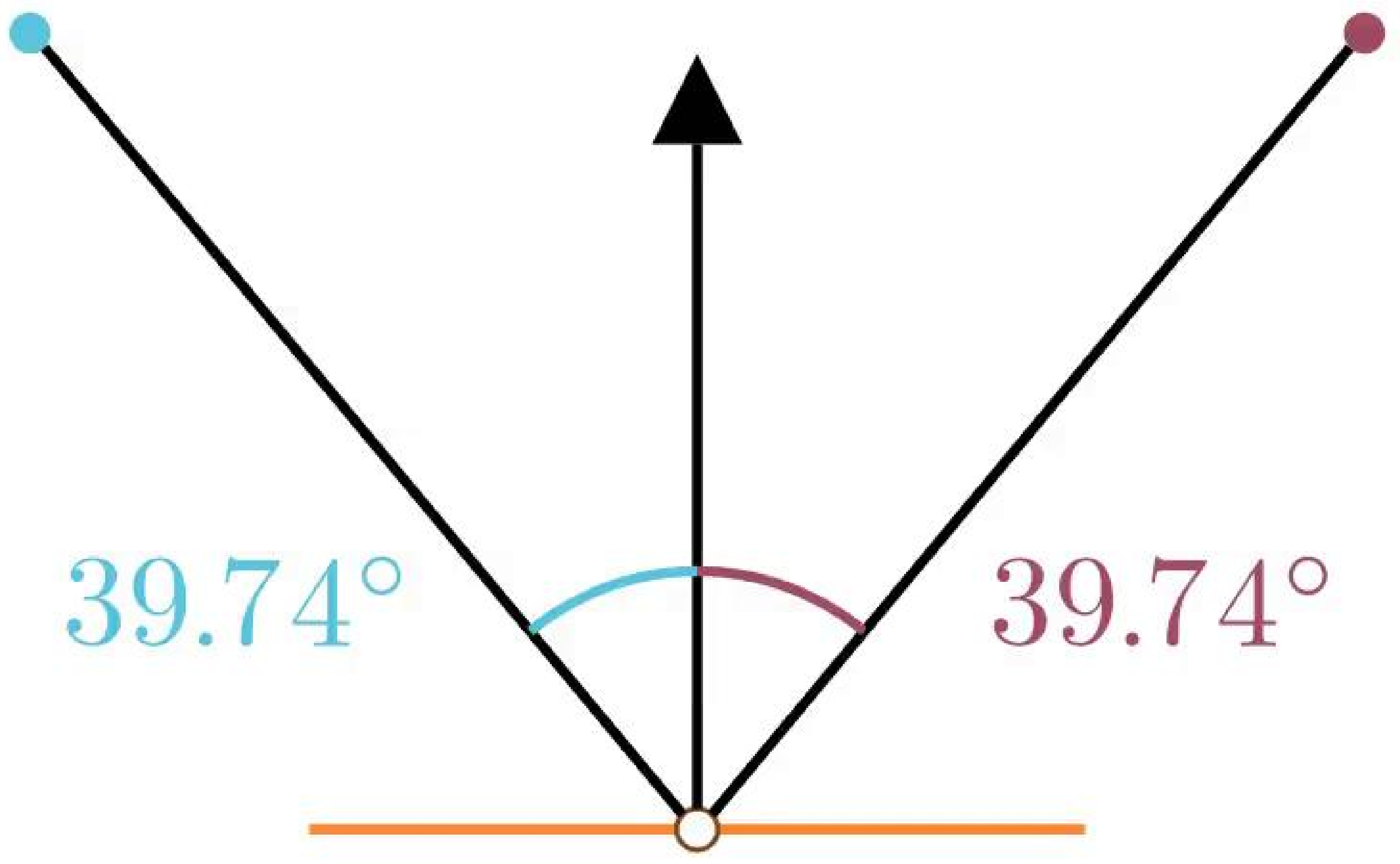

$$\mathcal{C} = \underbrace{0.00}_{\mathcal{I}}$$

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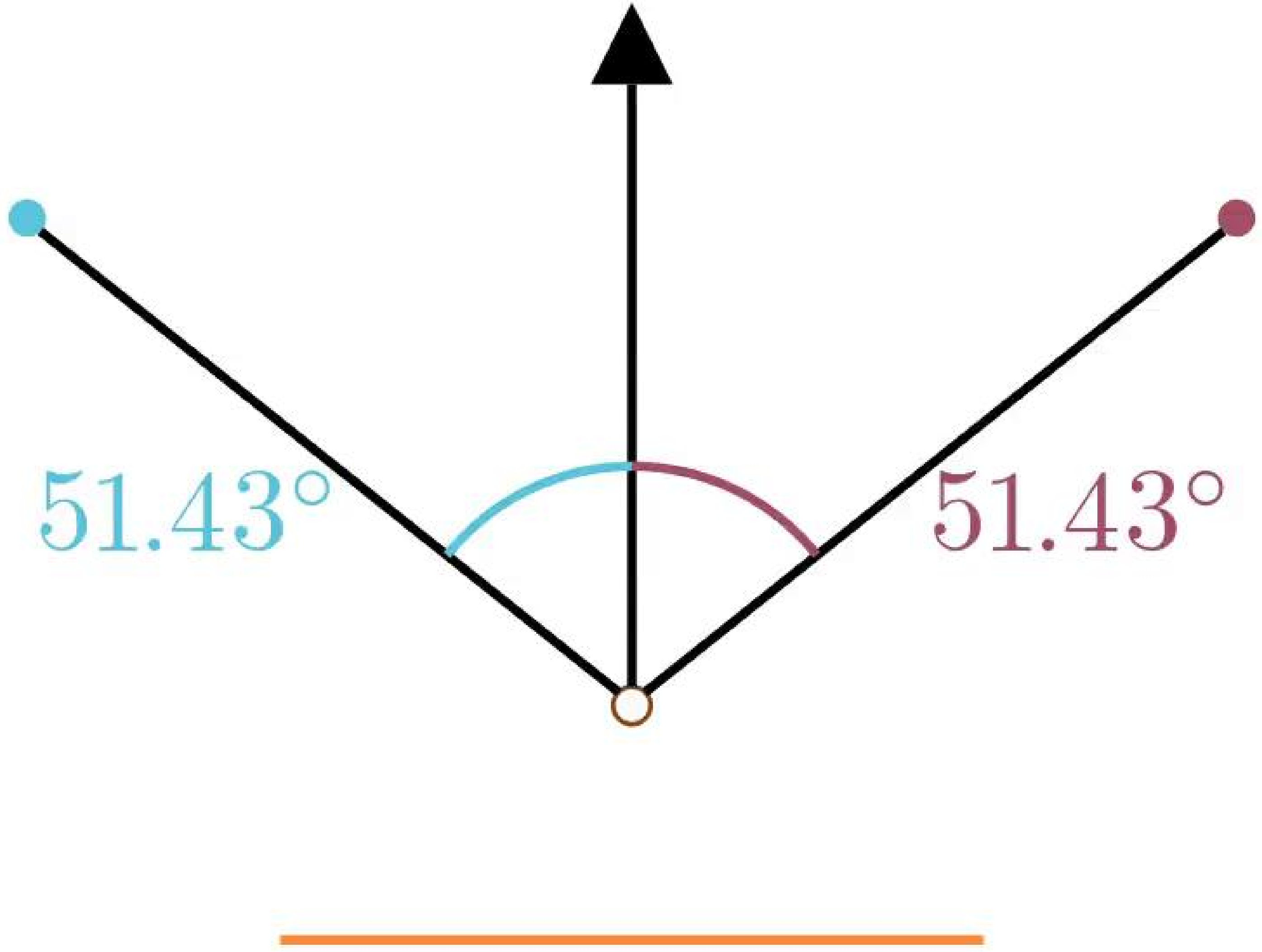

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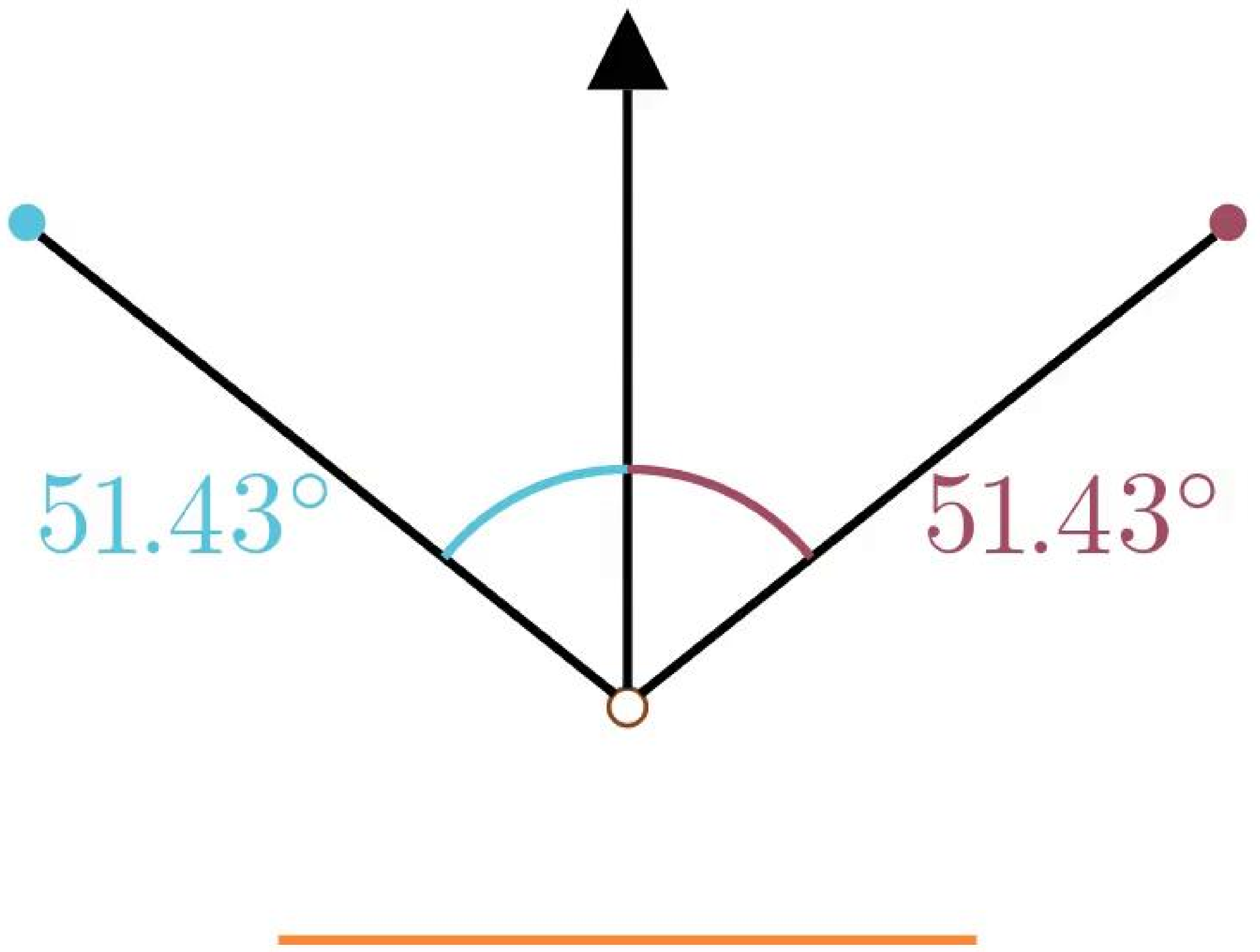

$$\mathcal{C} = \underbrace{0.00}_{\mathcal{I}} + \underbrace{1.00}_{\mathcal{F}}$$

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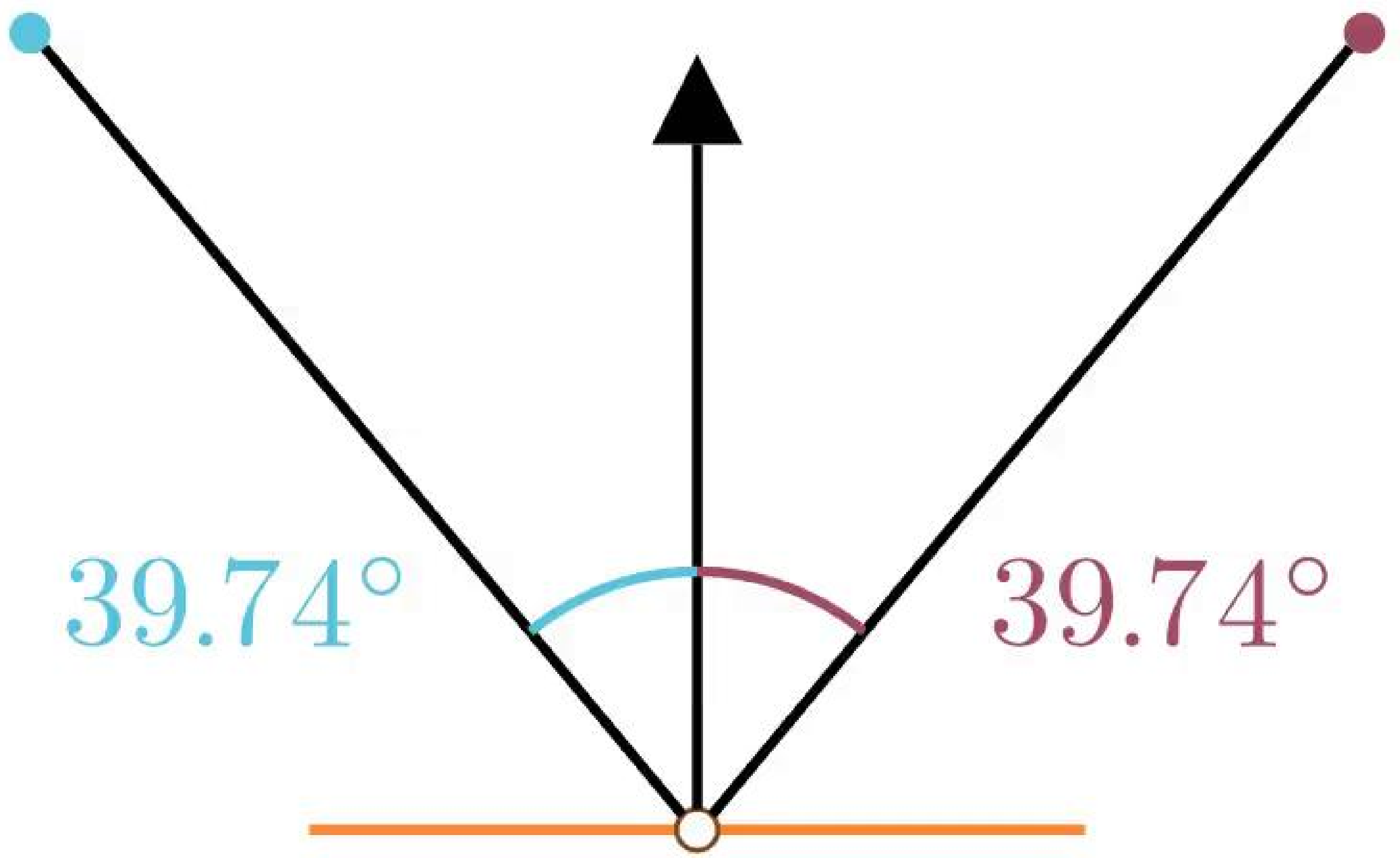

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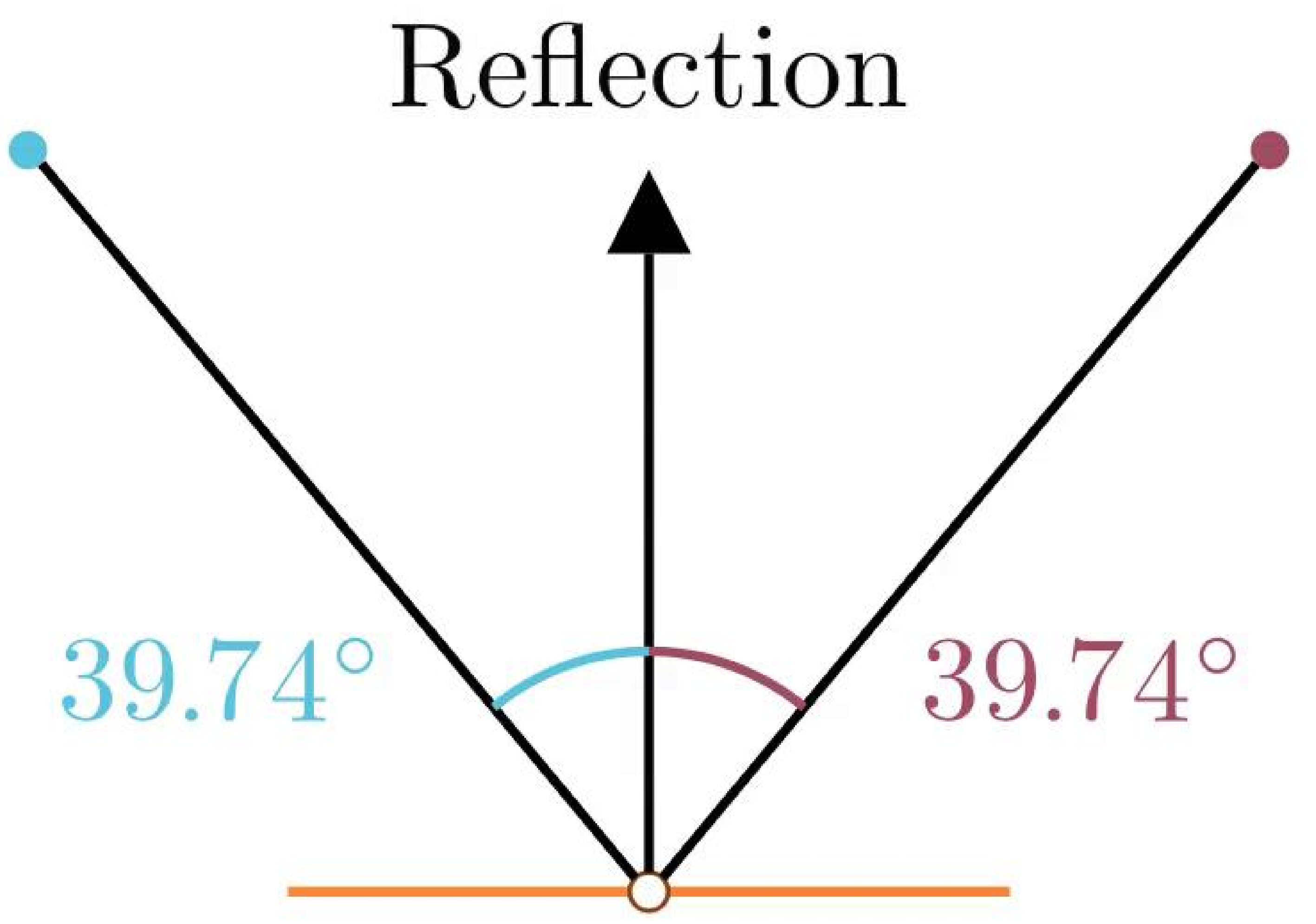
$$\mathcal{I} \sim \hat{\boldsymbol{r}} = \hat{\boldsymbol{i}} - 2\langle \hat{\boldsymbol{i}}, \hat{\boldsymbol{n}} \rangle \hat{\boldsymbol{n}}$$



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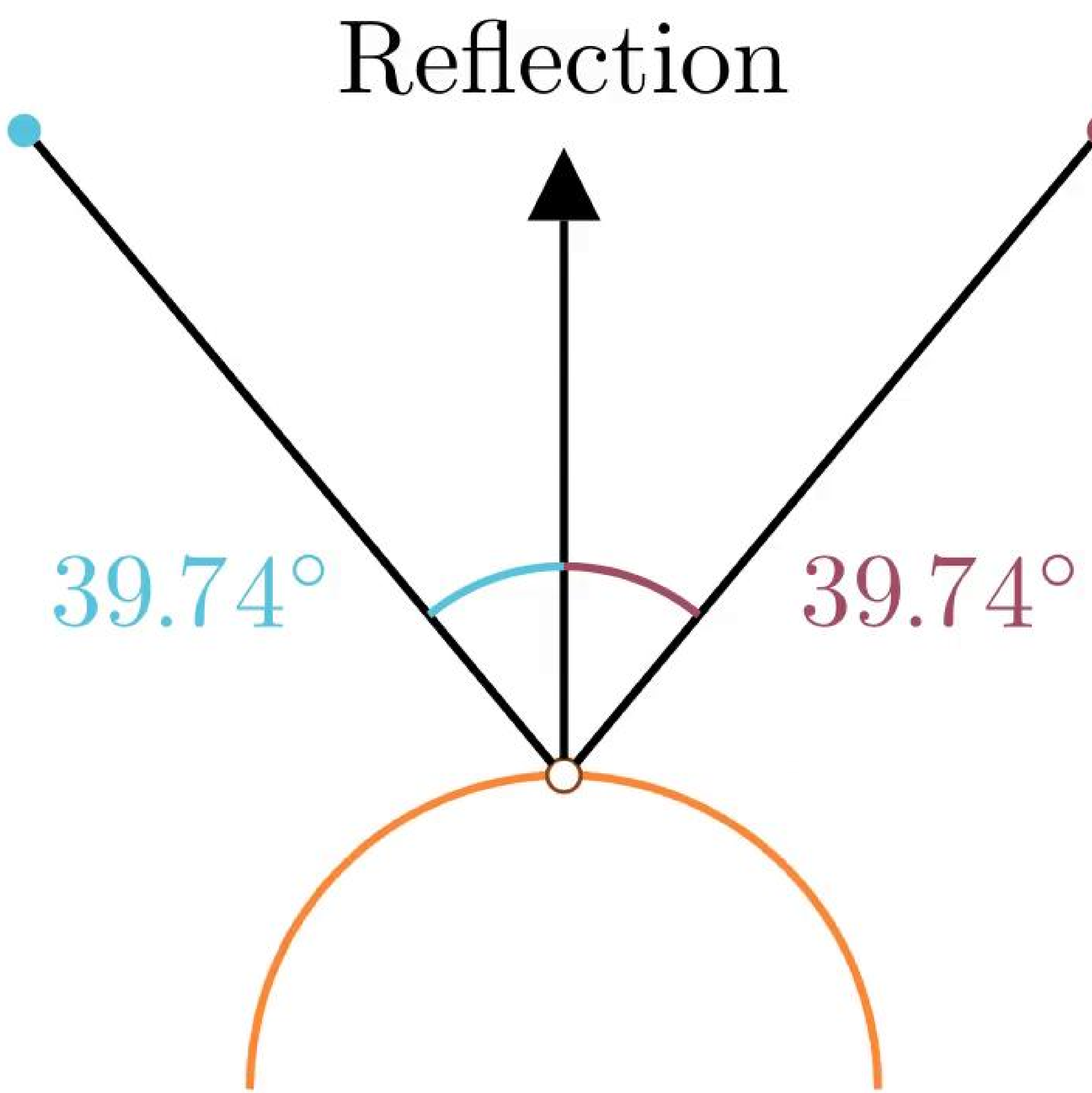
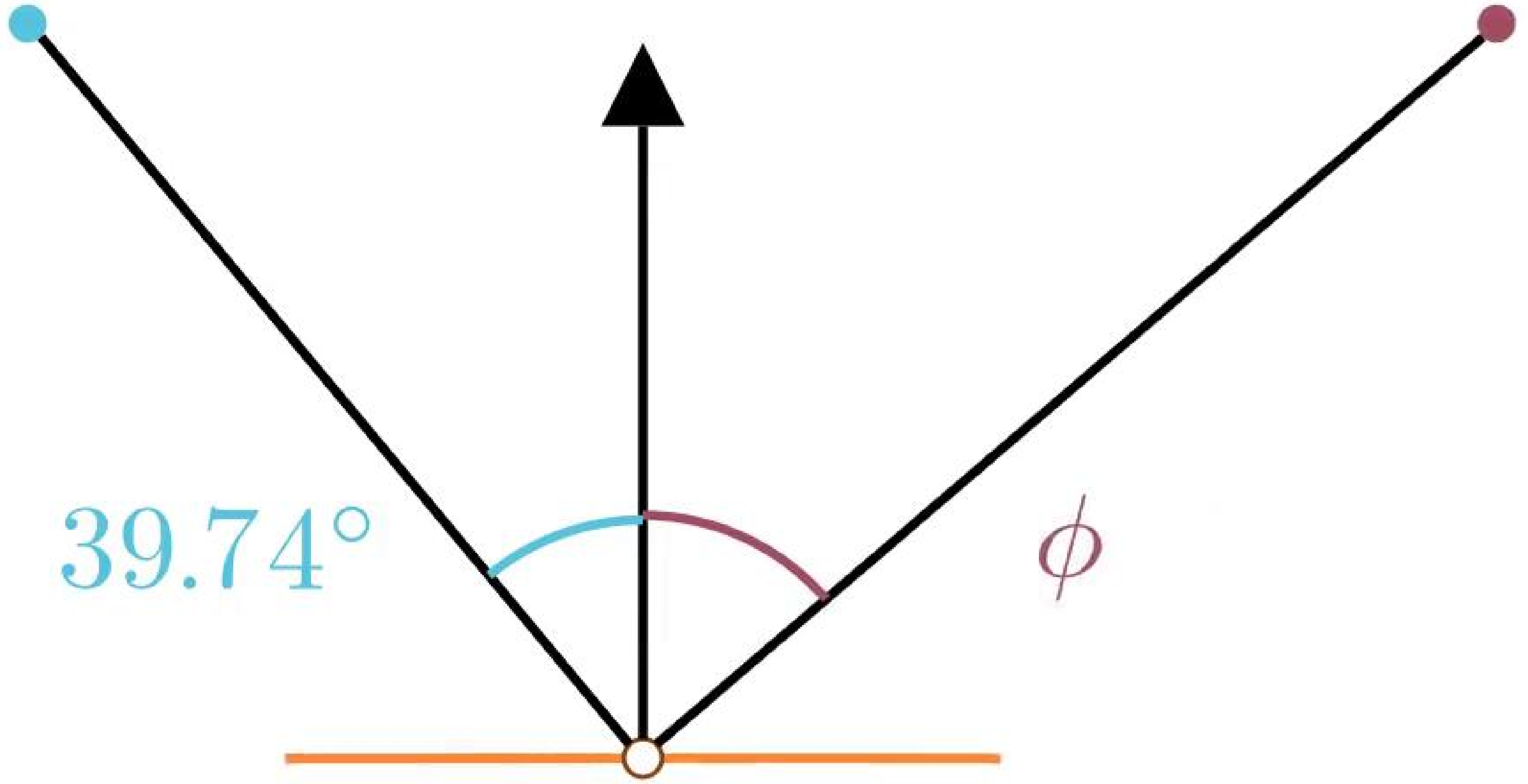


3. Min-Path-Tracing

$$\mathcal{I} \sim \boldsymbol{r} = f(\hat{\boldsymbol{n}}, \phi)$$

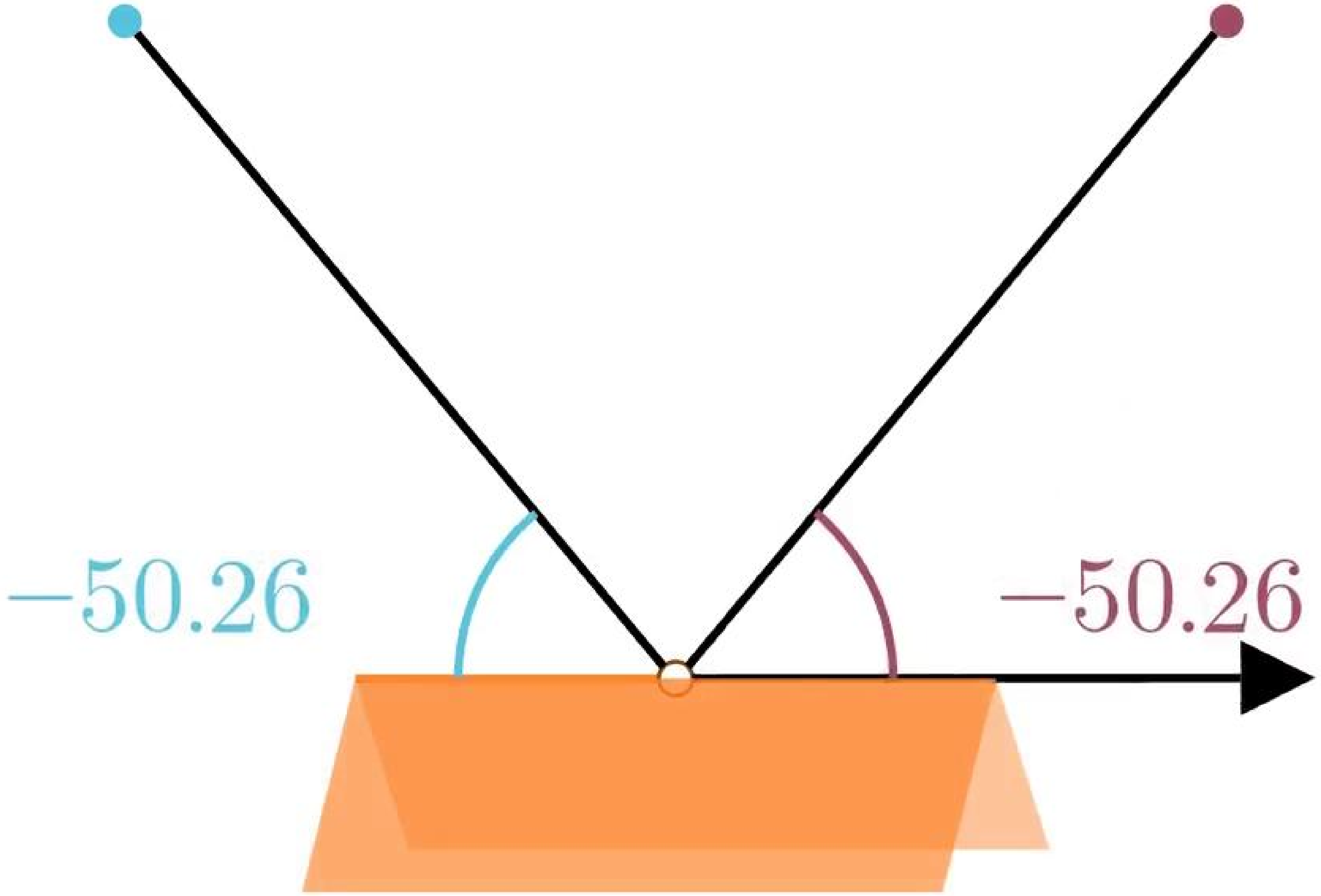
Reflection on metasurfaces



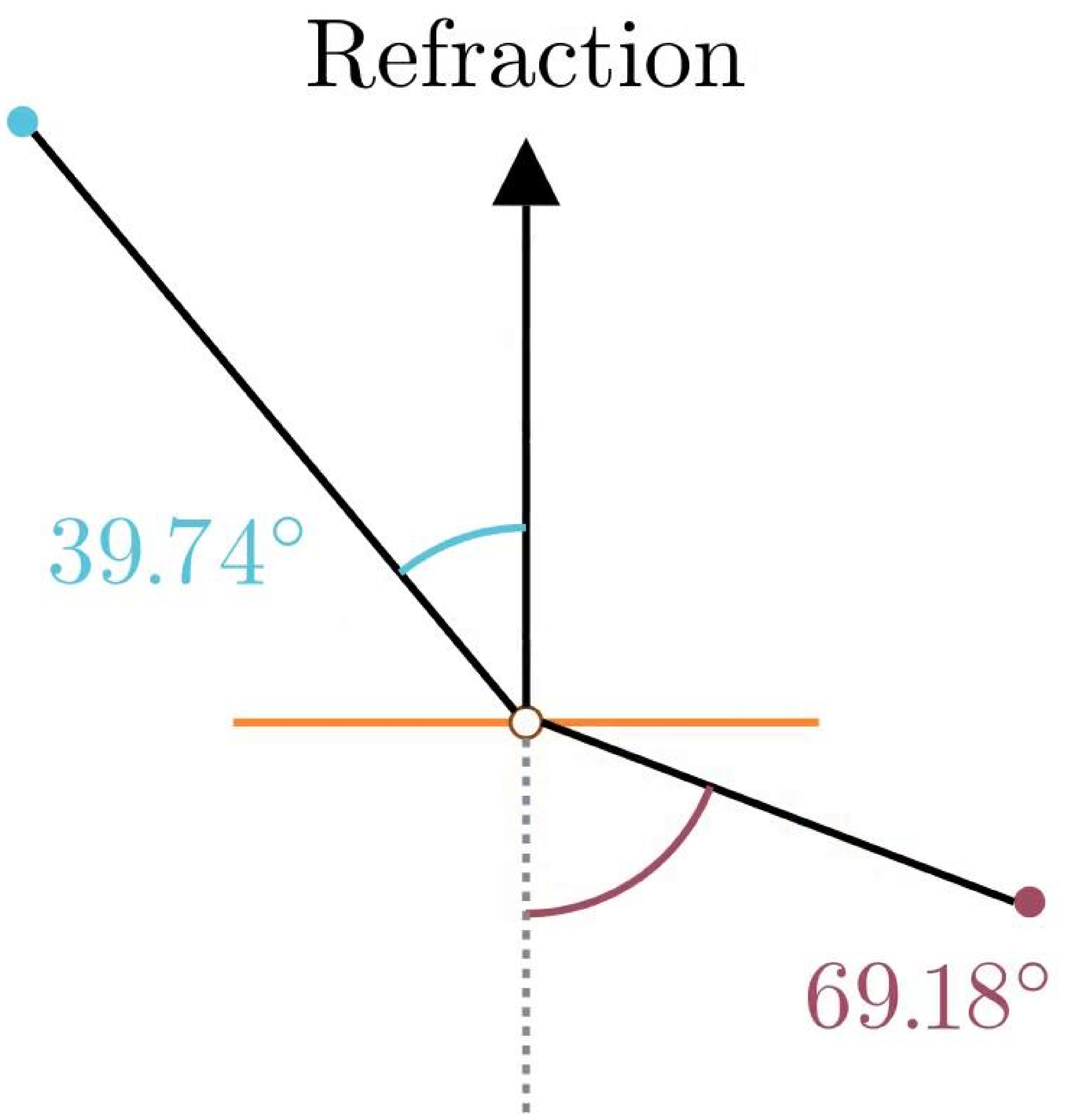
3. Min-Path-Tracing

$$\mathcal{I} \sim \frac{\langle \boldsymbol{i}, \hat{\boldsymbol{e}} \rangle}{\|\boldsymbol{i}\|} = \frac{\langle \boldsymbol{d}, \hat{\boldsymbol{e}} \rangle}{\|\boldsymbol{d}\|}$$

Diffraction



3. Min-Path-Tracing $\mathcal{I} \sim v_1 \sin(\theta_2) = v_2 \sin(\theta_1)$



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where n_t is the total number of unknowns

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$$\mathcal{C}(\boldsymbol{\mathcal{X}}) = 0$$

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$$\mathcal{C}(\boldsymbol{\mathcal{X}}) \leq \epsilon$$

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If we know a mapping s.t. $(x_k, y_k) \leftrightarrow t_k$

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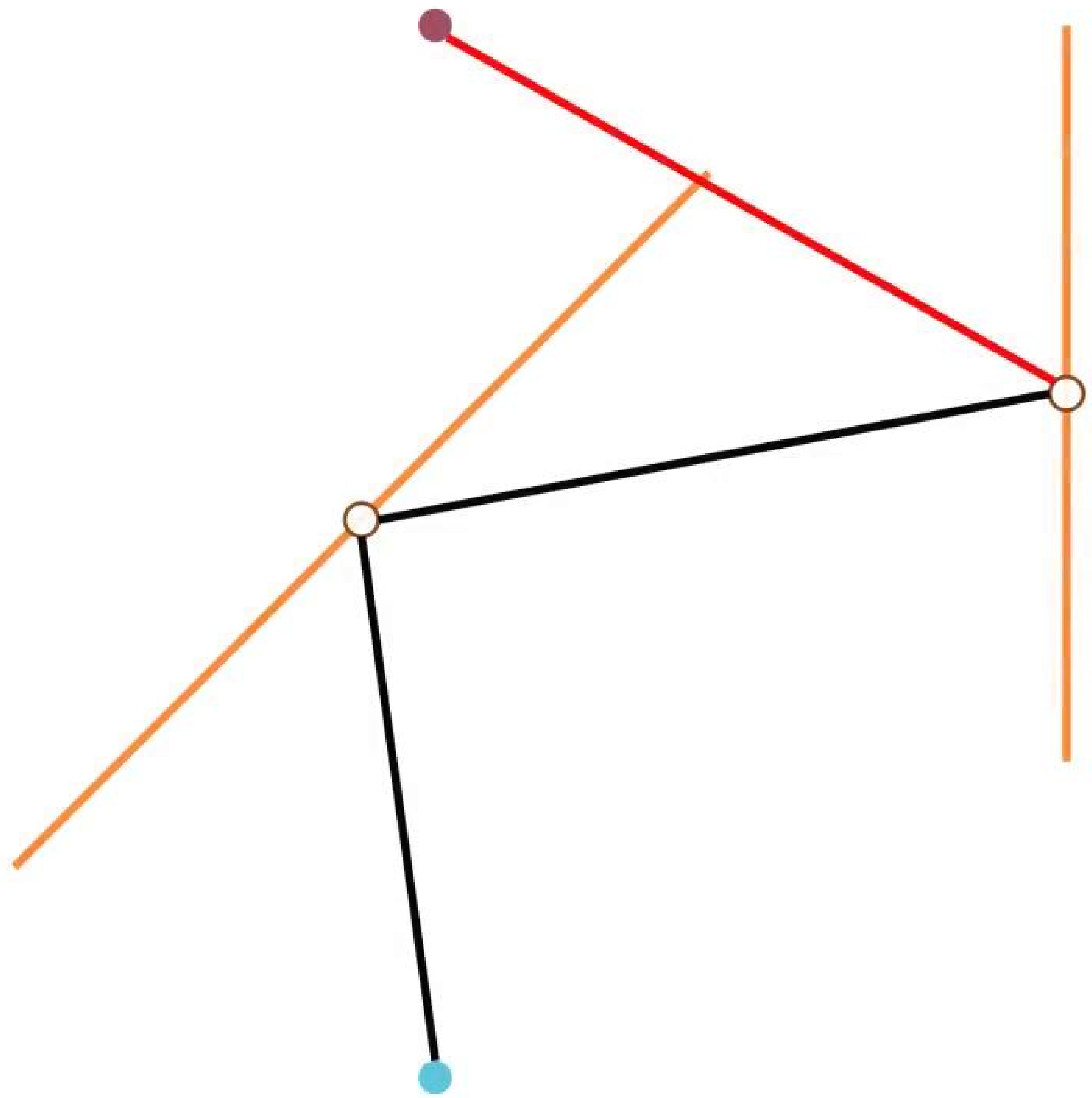
If we know a mapping s.t. $(x_k, y_k) \leftrightarrow t_k$

$$\underset{\boldsymbol{\mathcal{T}} \in \mathbb{R}^{n_r}}{\text{minimize}}\ \mathcal{C}(\boldsymbol{\mathcal{X}}(\boldsymbol{\mathcal{T}})) := \|\mathcal{I}(\boldsymbol{\mathcal{X}}(\boldsymbol{\mathcal{T}}))\|^2$$

where n_r is the total number of (2d) reflections

$$\mathcal{C}(\boldsymbol{\mathcal{X}}(\boldsymbol{\mathcal{T}})) \leq \epsilon$$

3. Min-Path-Tracing



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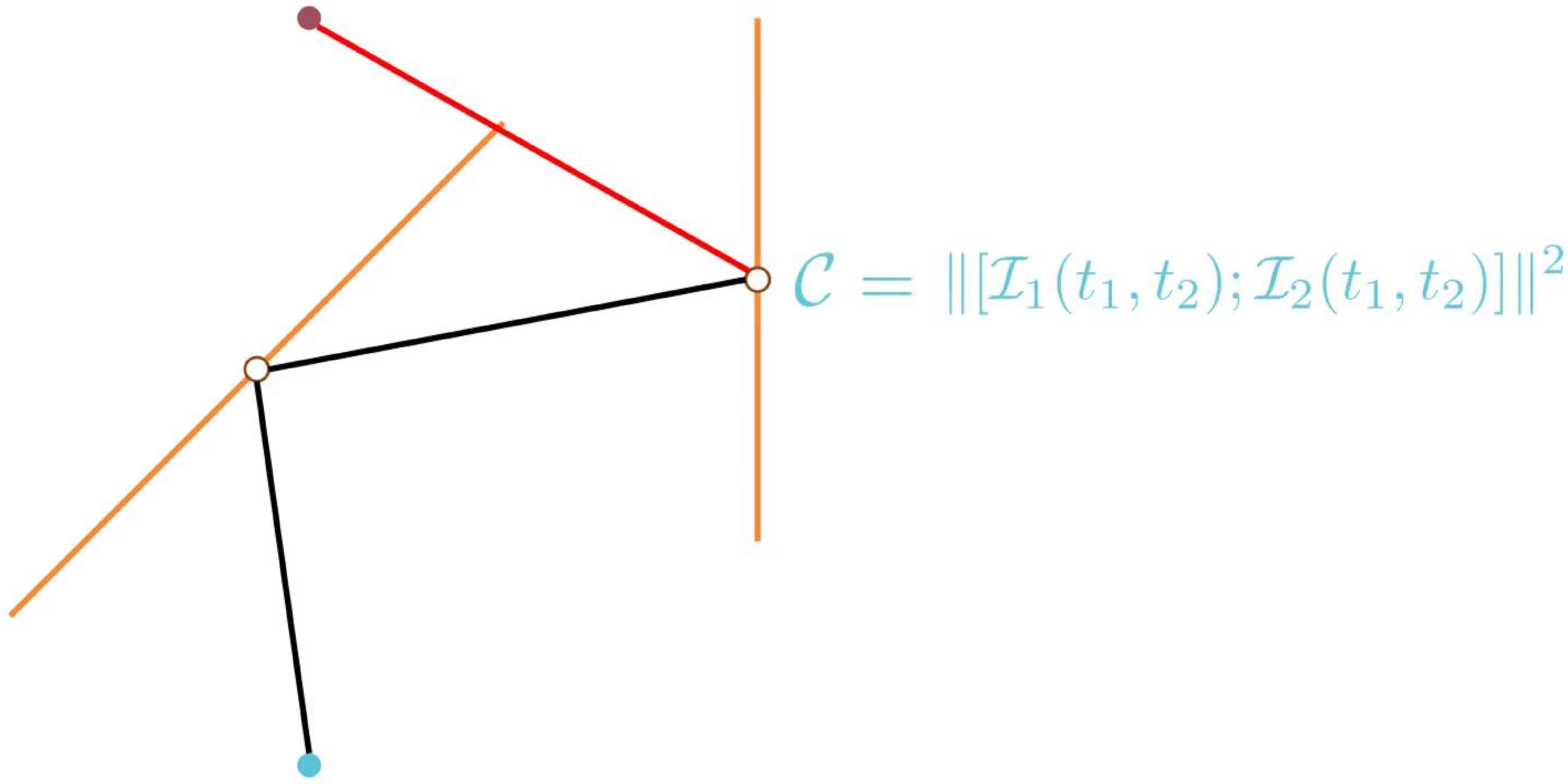

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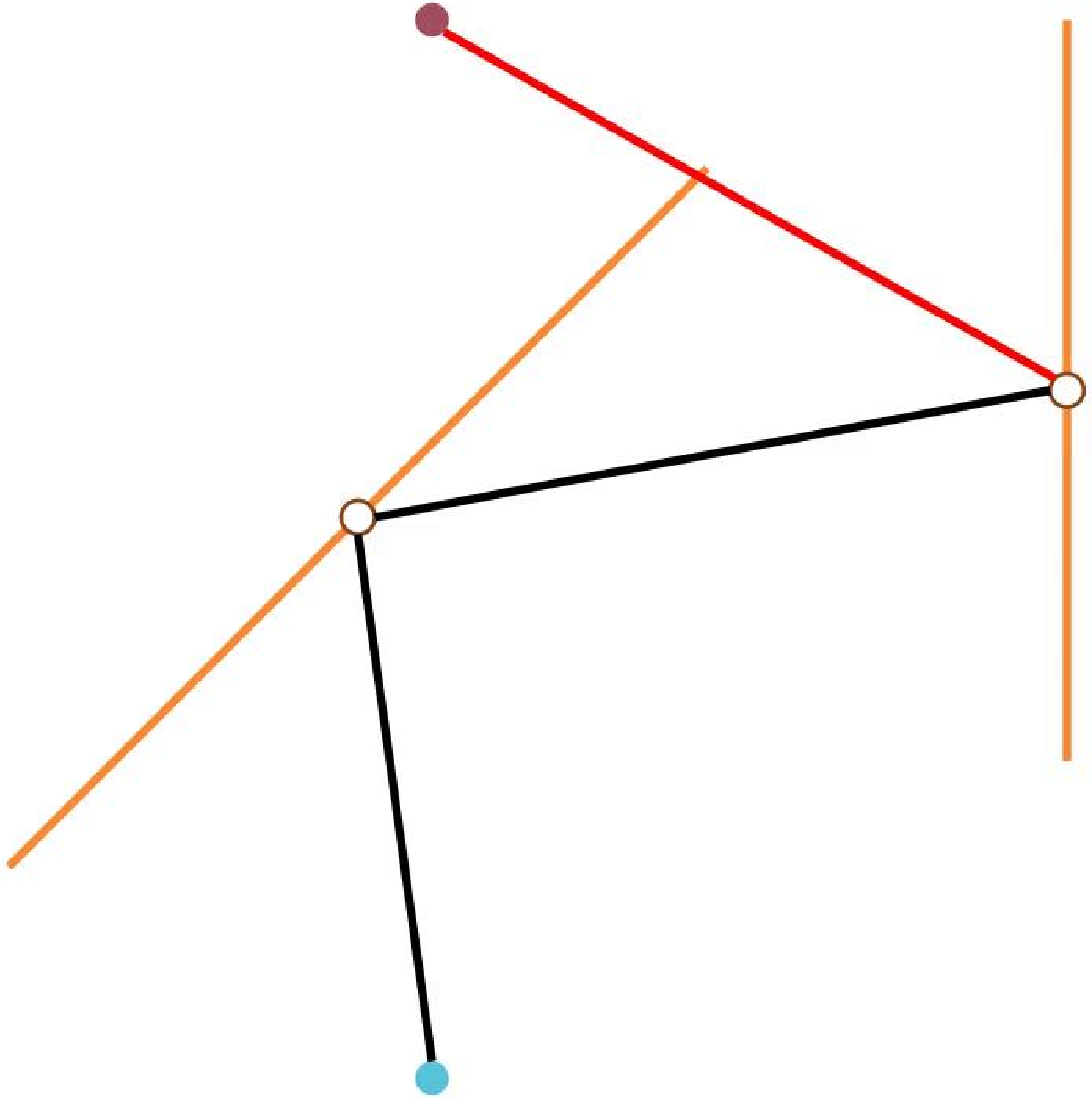
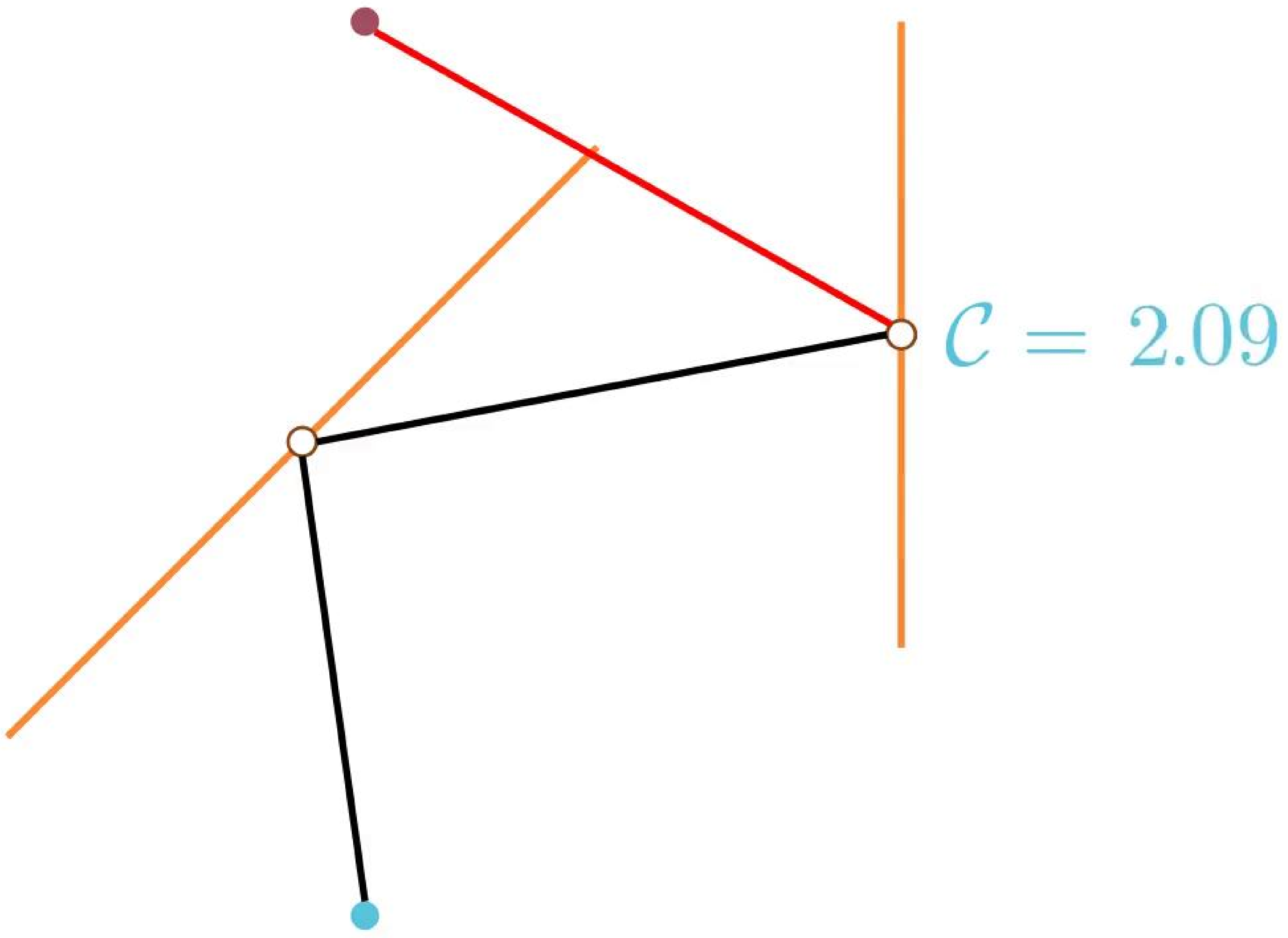


$$
\begin{aligned}
\mathcal{C} = & \left(-t_1 + t_2 + \frac{(t_2-4)\sqrt{(t_1-5)^2+(t_1-t_2)^2}}{\sqrt{(t_2-4)^2+9}}\right)^2 \\
& + \left(t_1 + \frac{3\sqrt{(t_1-5)^2+(t_1-t_2)^2}}{\sqrt{(t_2-4)^2+9}} - 5\right)^2 \\
& + \left|t_1 + \frac{(t_1-5)\sqrt{(t_1-2)^2+(t_1+1)^2}}{\sqrt{(t_1-5)^2+(t_1-t_2)^2}} - \frac{\sqrt{2}\left(\sqrt{2}(t_1-2)-\sqrt{2}(t_1+1)\right)}{2} - 2\right|^2 \\
& + \left|t_1 + \frac{(t_1-t_2)\sqrt{(t_1-2)^2+(t_1+1)^2}}{\sqrt{(t_1-5)^2+(t_1-t_2)^2}} + \frac{\sqrt{2}\left(\sqrt{2}(t_1-2)-\sqrt{2}(t_1+1)\right)}{2} + 1\right|^2
\end{aligned}
$$

3. Min-Path-Tracing



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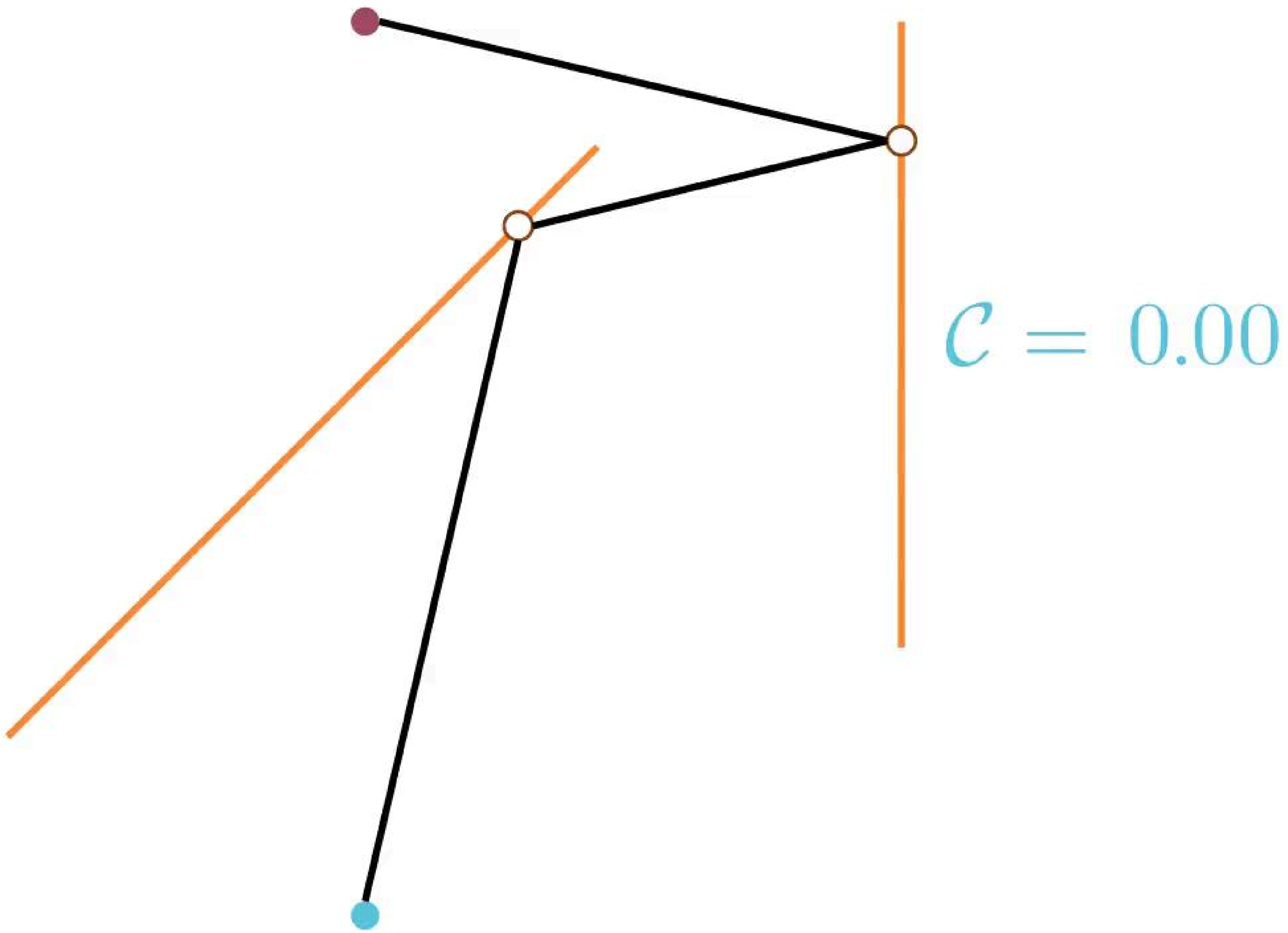
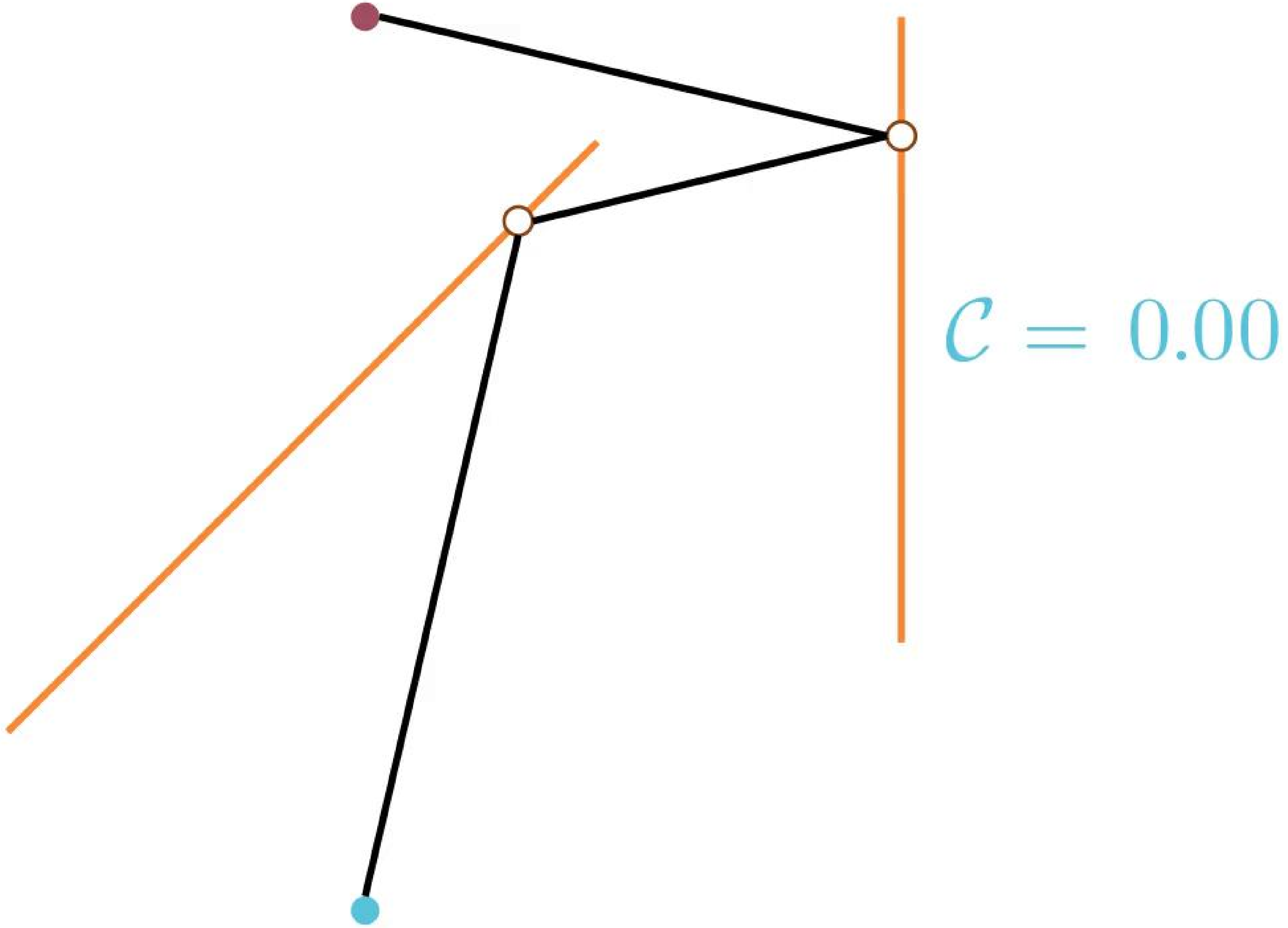


3. Min-Path-Tracing

What if we had a metasurface?



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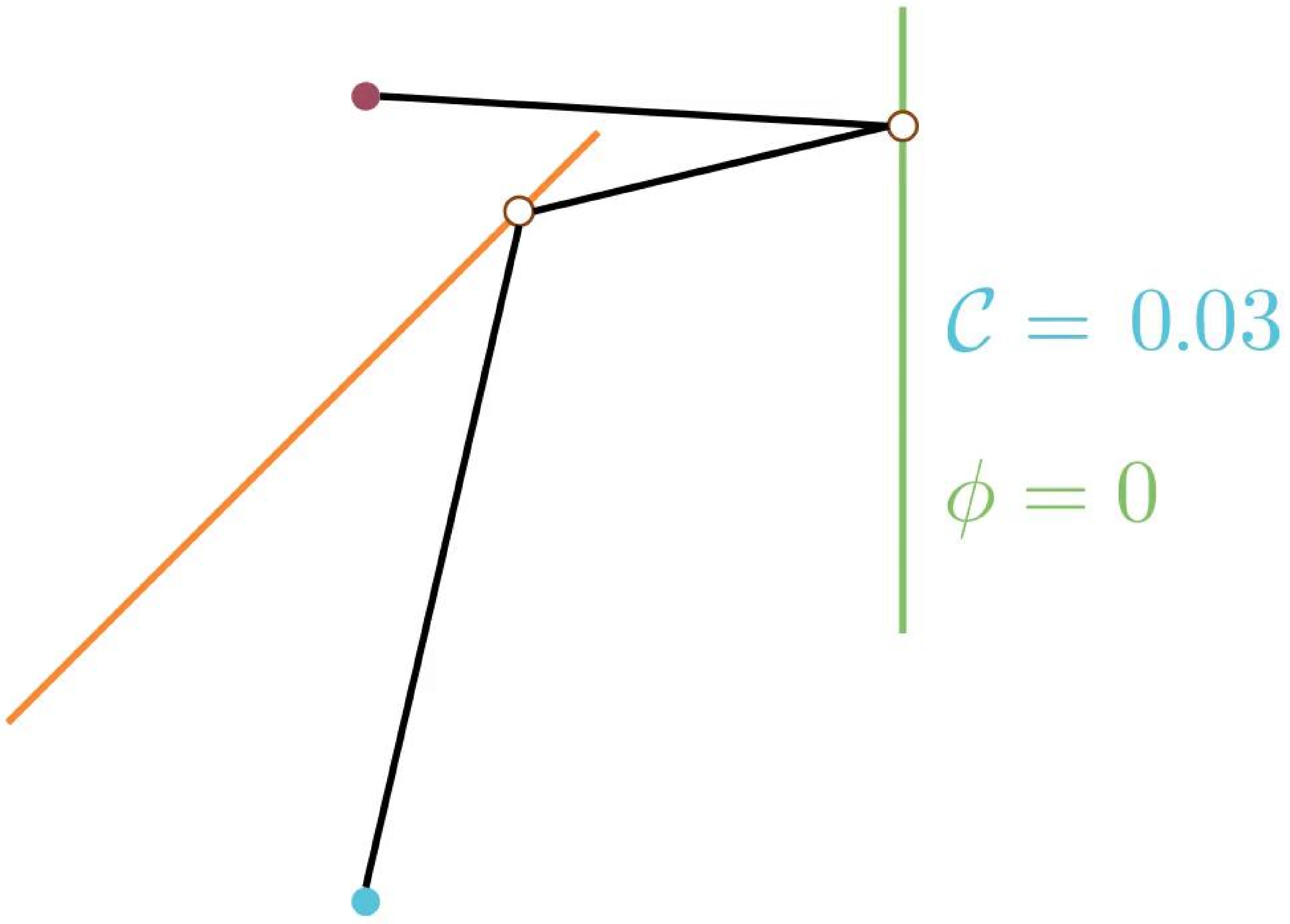

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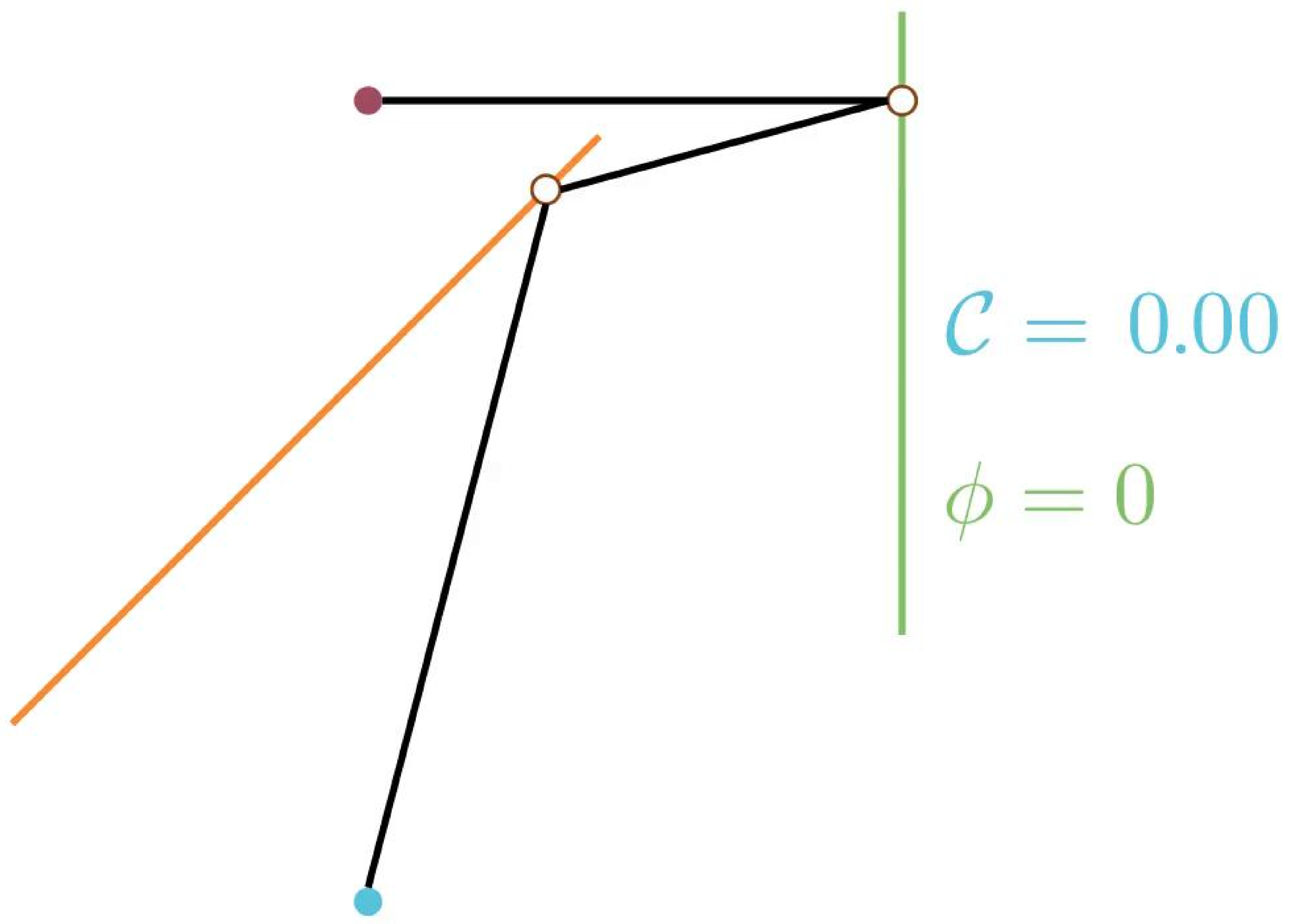

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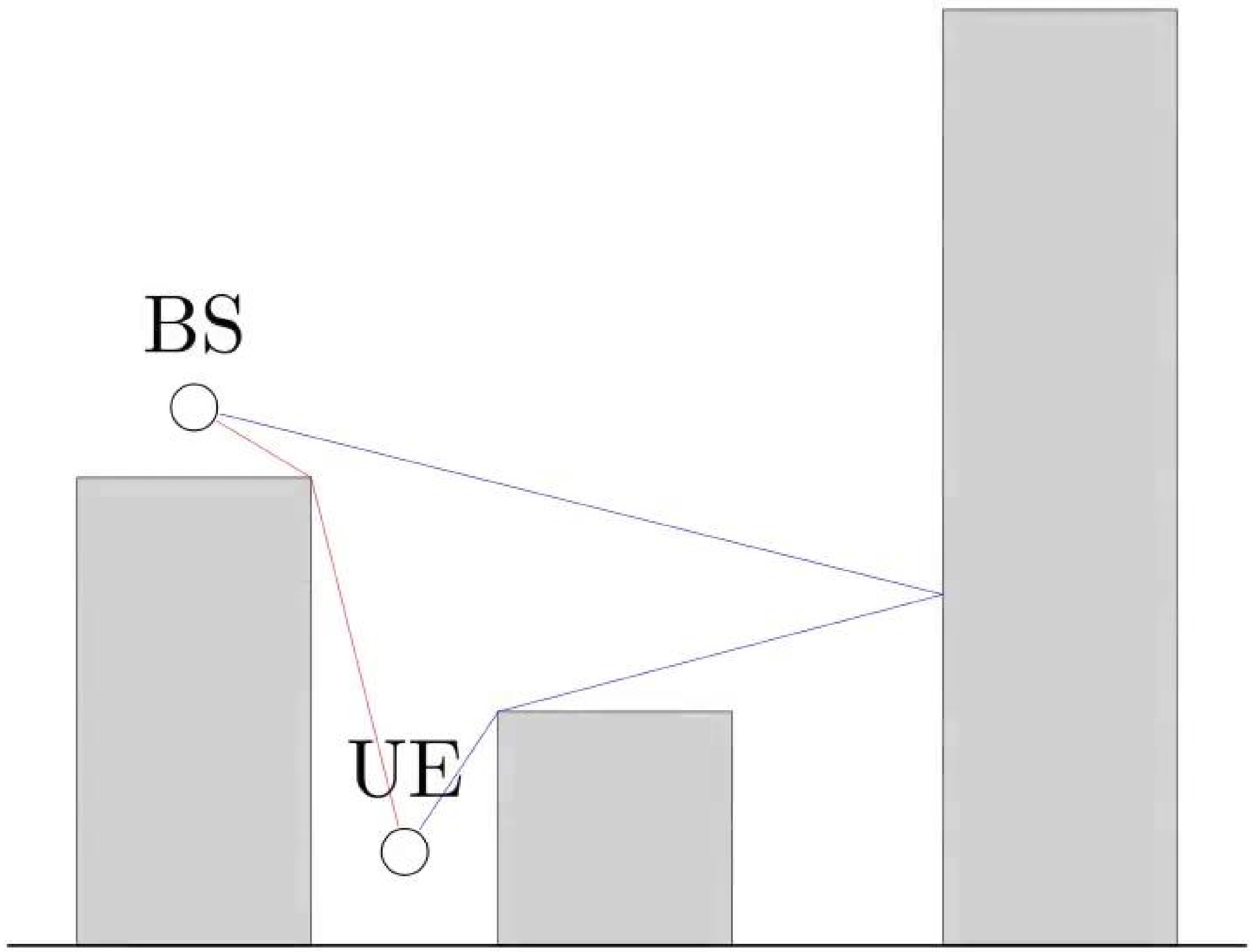

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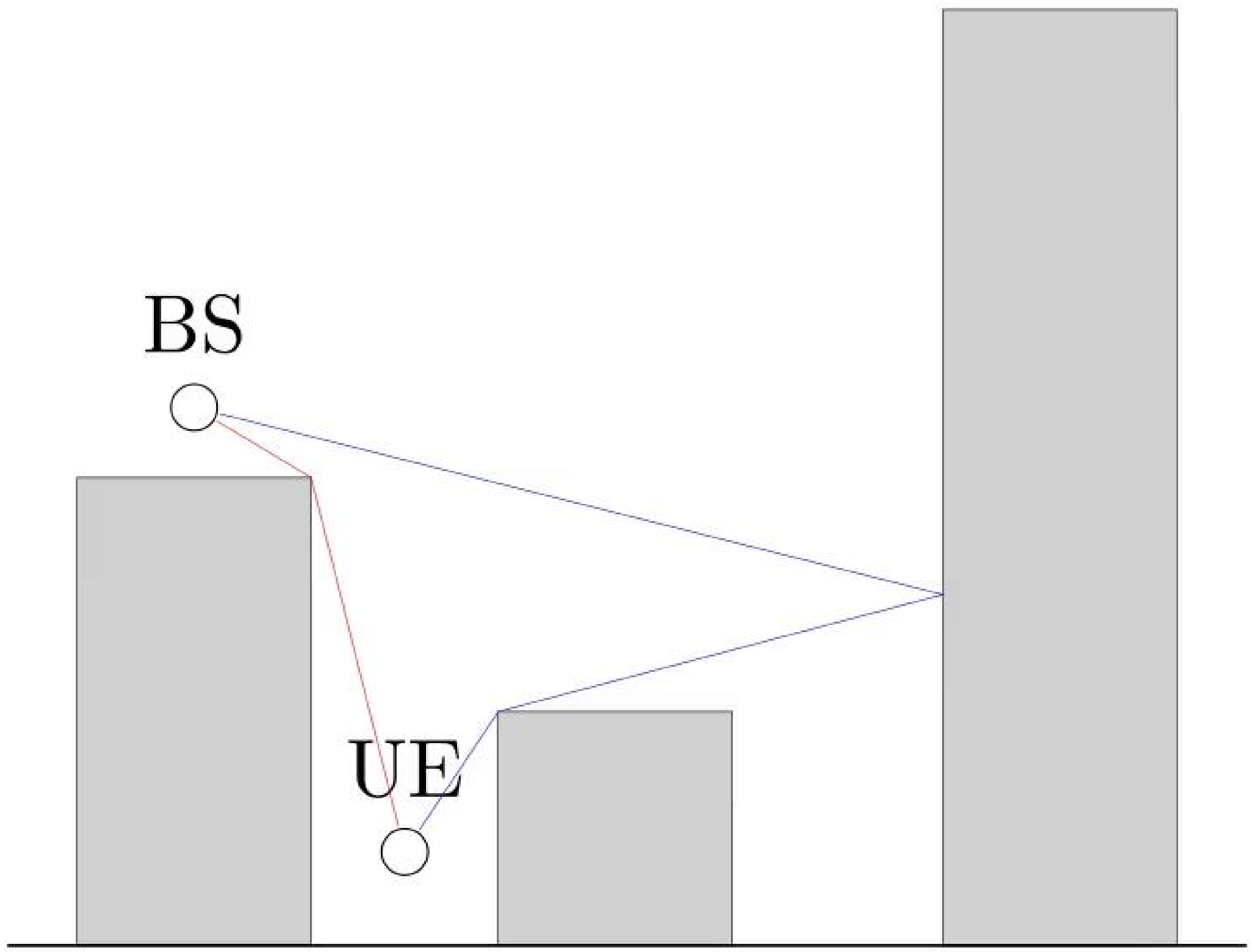

Number of interactions	1	2			3						
Interactions list	D	RD	DR	DD	RRD	RDR	RDD	DRR	DRD	DDR	DDD
E/E_{LOS} (dB)	**-32**	-236	-242	**-44**	-231	-246	**-69**	-212	**-72**	-81	**-60**

Summary:

Summary:

Pros

- Any geometry (but requires more info.)
- Any # of reflect., diff., and refract.
- Allows for multiple solutions
- Optimizer can be chosen

3. Min-Path-Tracing

Summary:

Pros

- Any geometry (but requires more info.)
- Any # of reflect., diff., and refract.
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Cons

- In general, problem is not convex
- Slower - $\mathcal{O}(k \cdot n)$

3. Min-Path-Tracing

MPT $\neq$ *Fermat*'s path:

$$\underset{\boldsymbol{\mathcal{X}} \in \mathbb{R}^{n_t}}{\text{minimize}}\ \mathcal{L}(\boldsymbol{\mathcal{X}}) := \sum_i \|\boldsymbol{\mathcal{X}_i} - \boldsymbol{\mathcal{X}_{i-1}}\|$$

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A Novel Ray Tracing Algorithm for Scenarios Comprising Pre-Ordered Multiple Planar Reflectors, Straight Wedges, and Vertexes

Federico Puggelli, Giorgio Carluccio, and Matteo Albani

4. About differentiability

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$$I = \sum_{p}^{\text{paths}} f(p, \theta)$$

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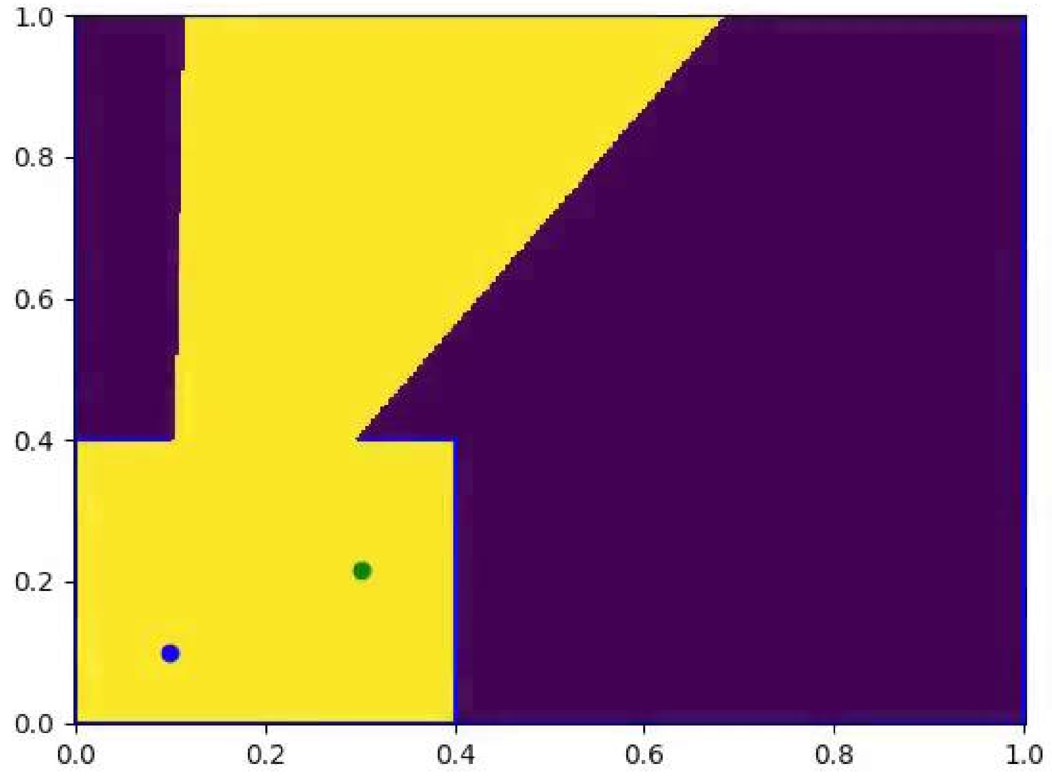
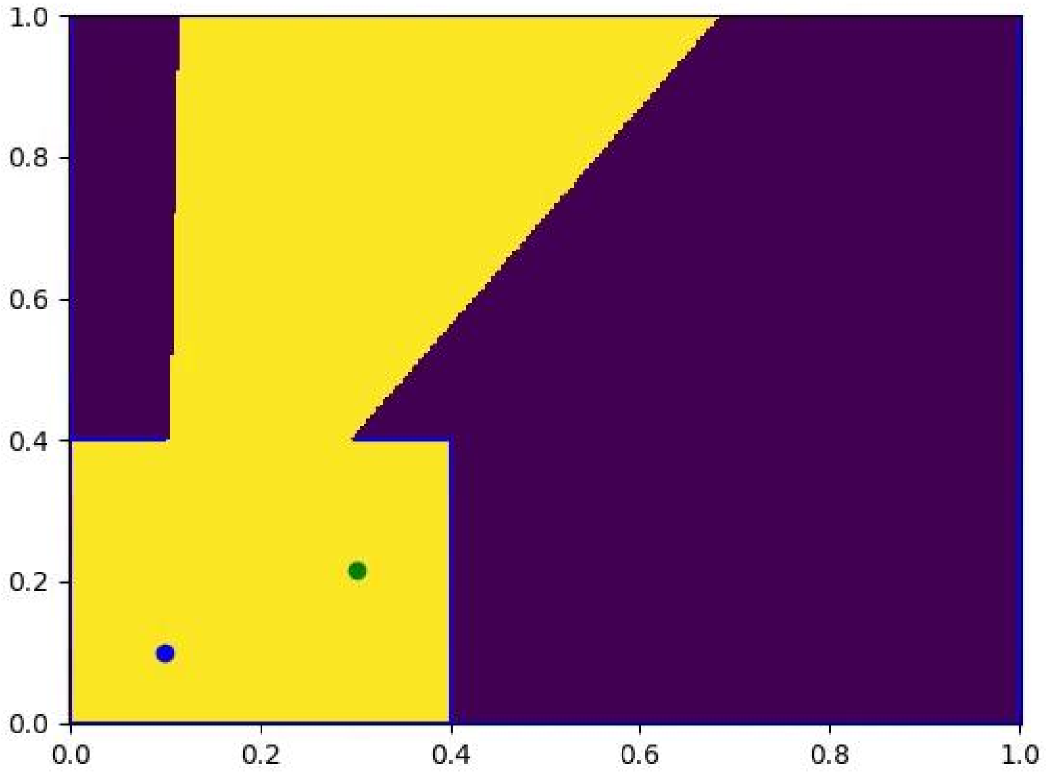


5. Current work



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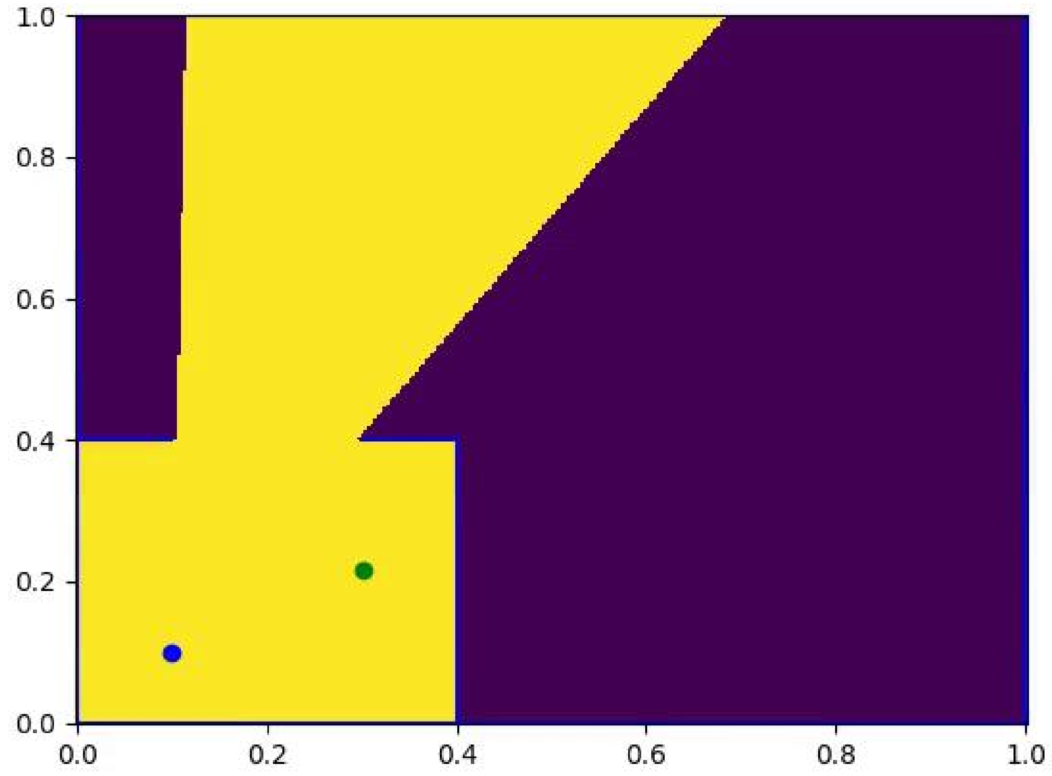

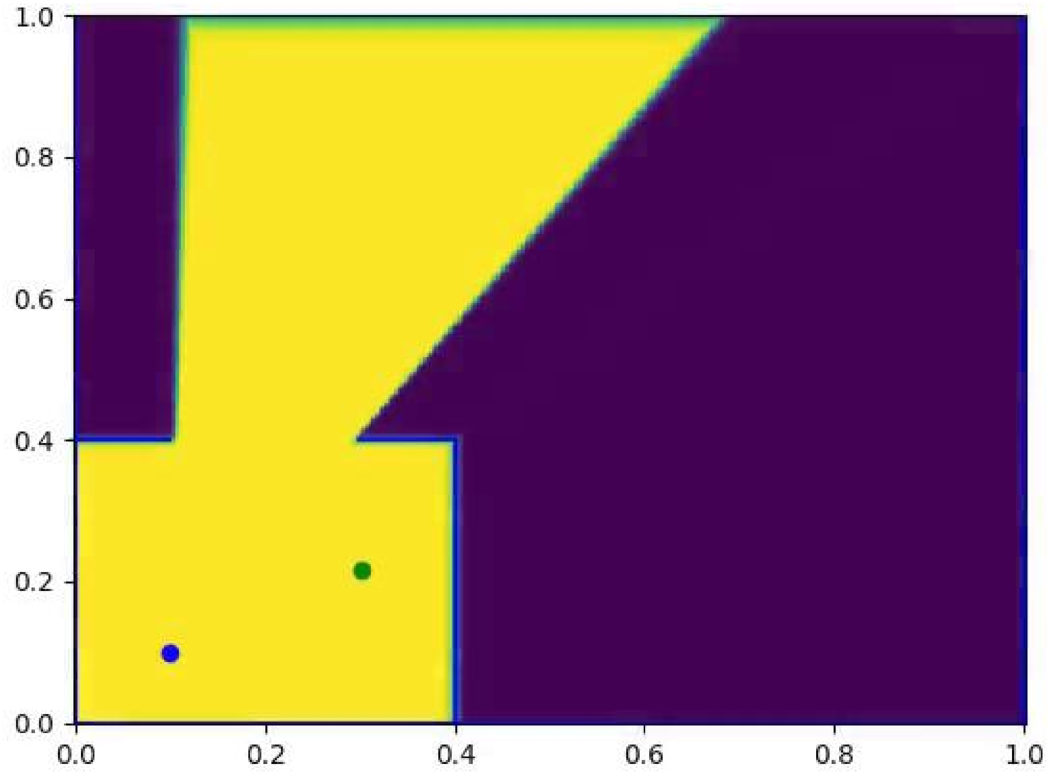

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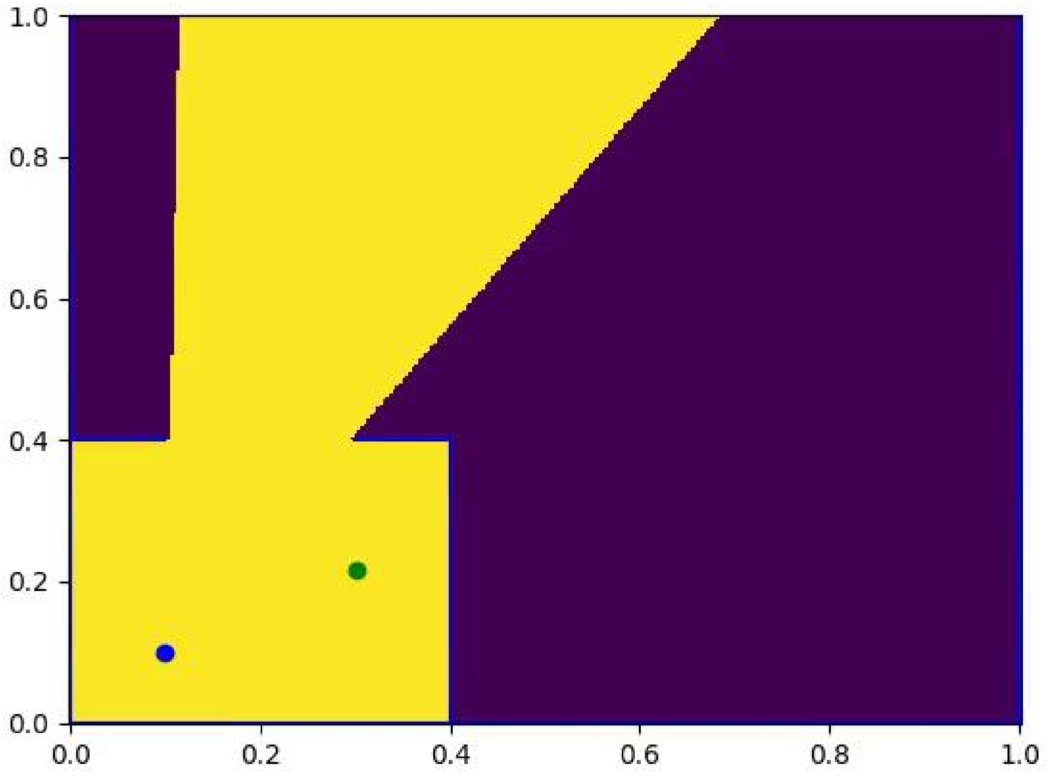

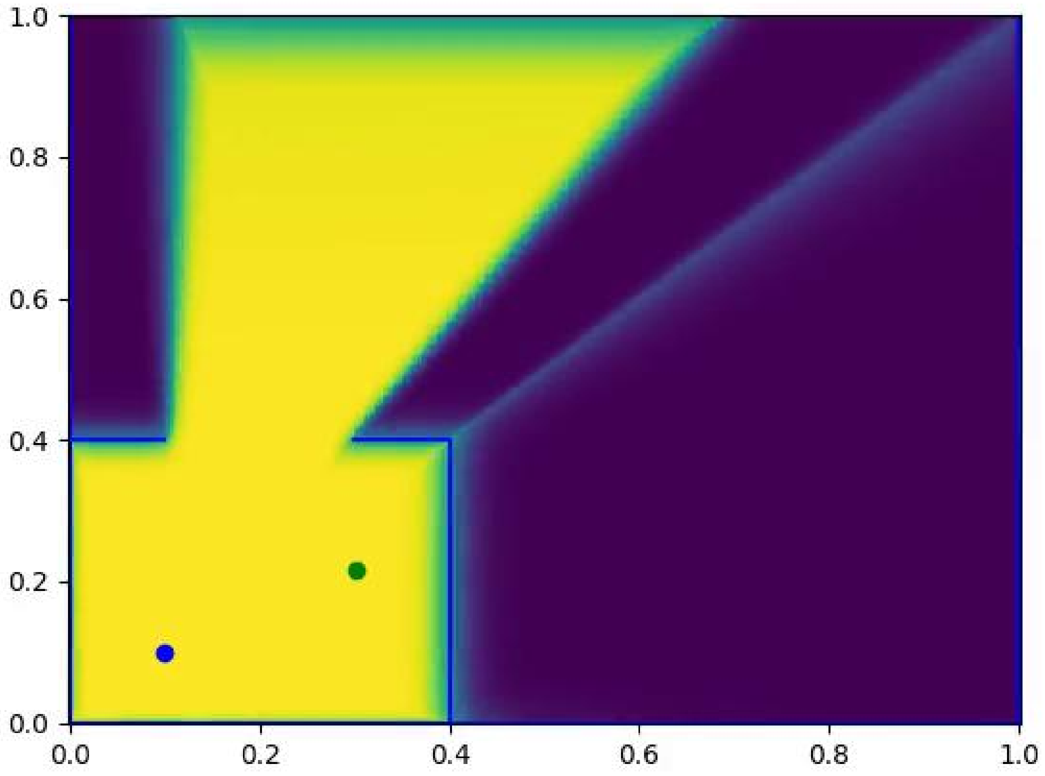

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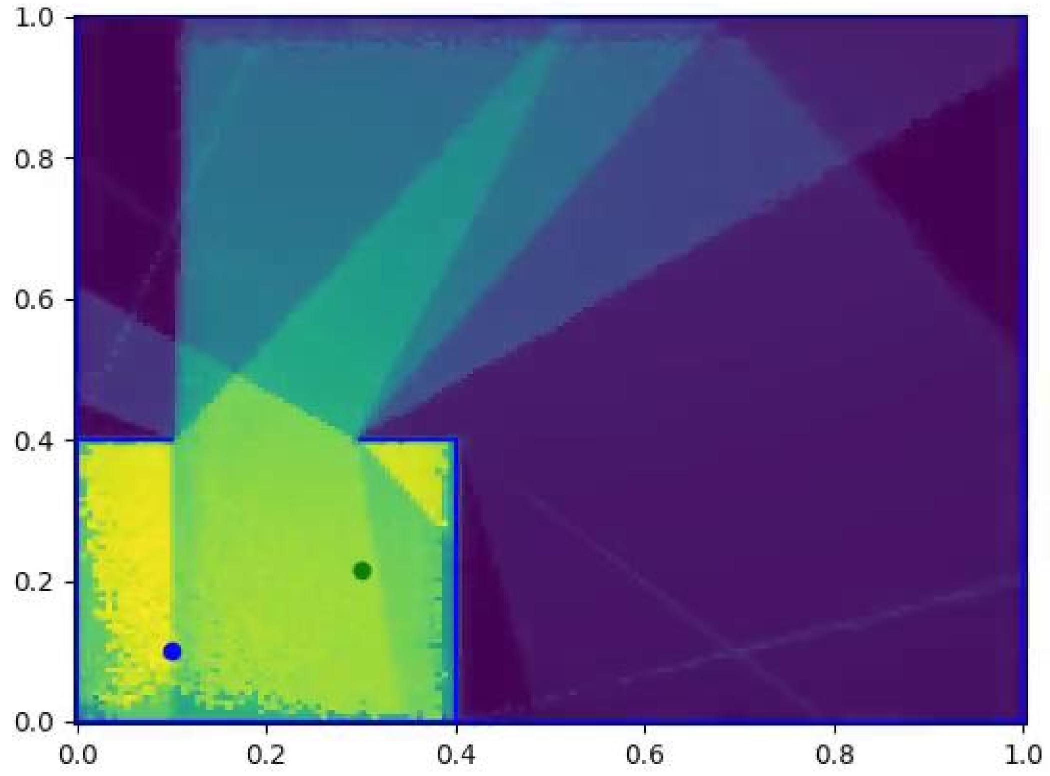

Thanks for listening!