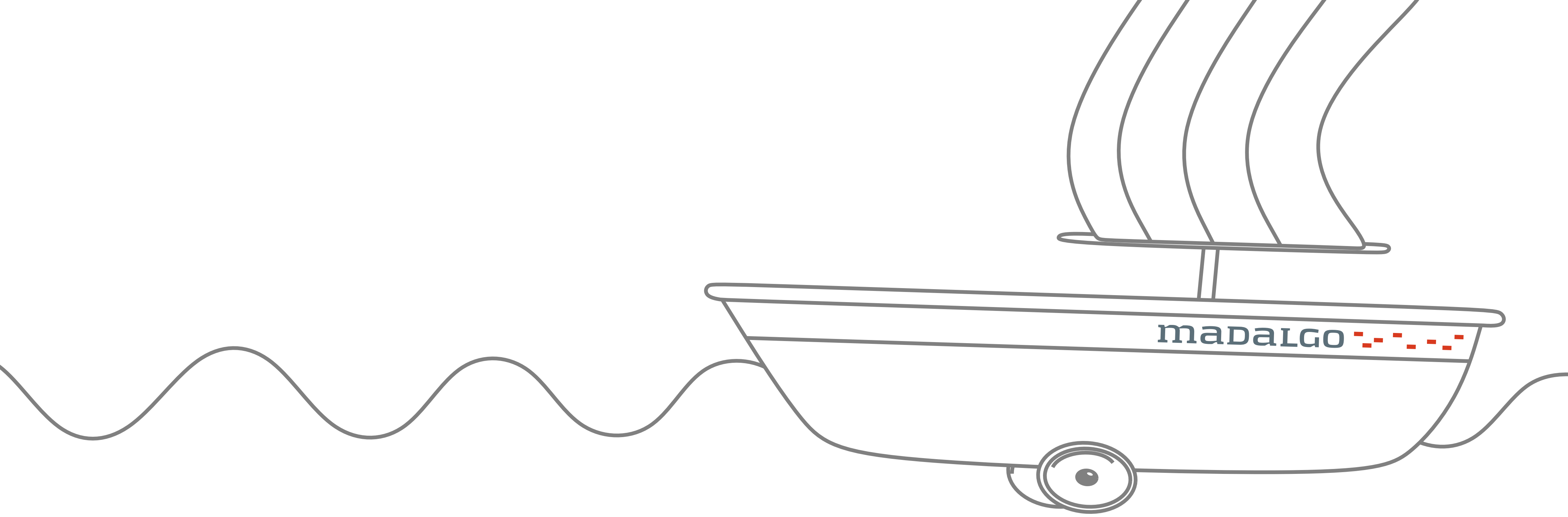


Cleaning massive sonar point clouds

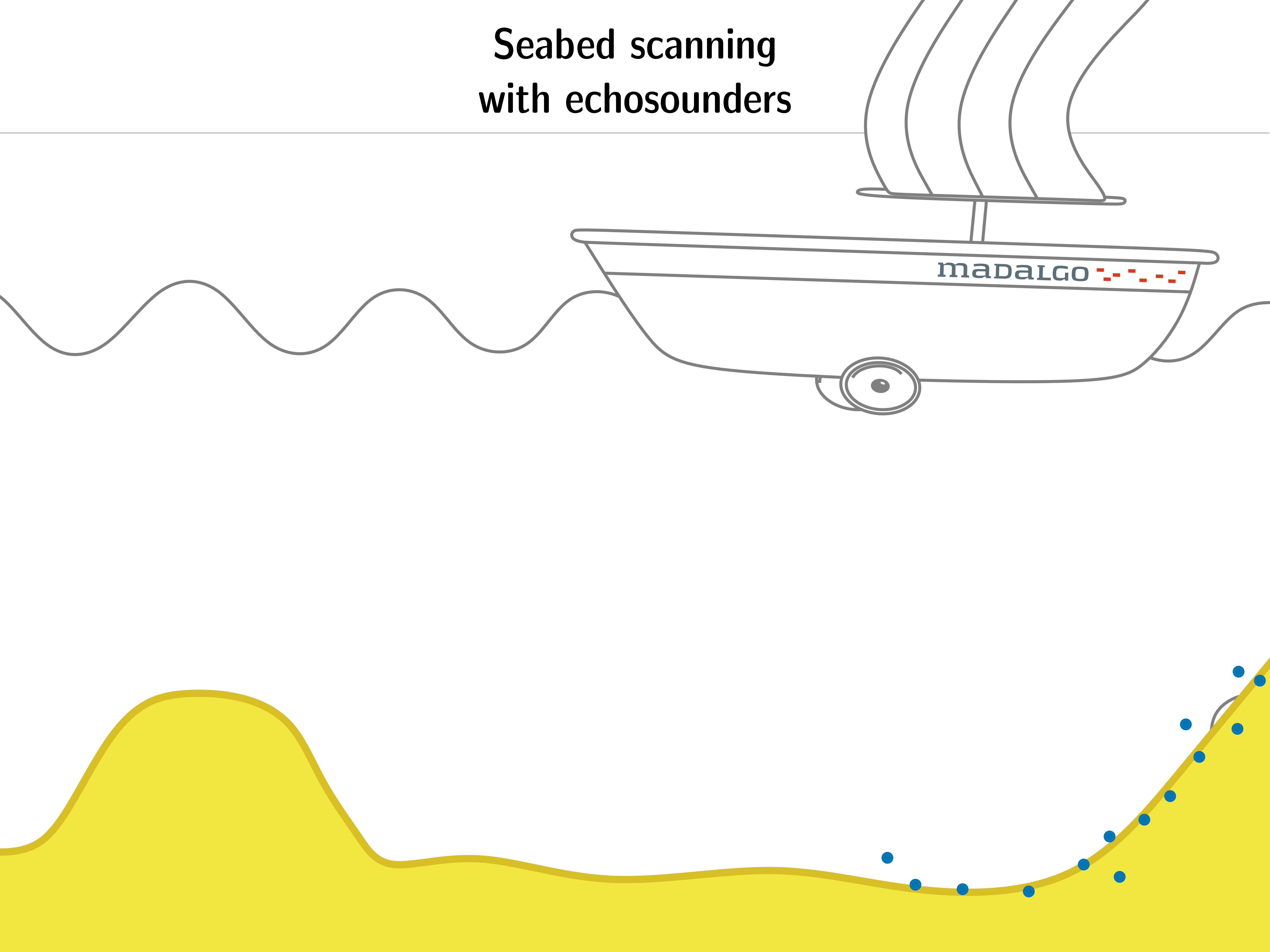
Lars Arge
Aarhus University

Kasper Green Larsen
Aarhus University

Thomas Mølhave
Duke University

<u>Freek van Walderveen</u>
Aarhus University

Seabed scanning with echosounders



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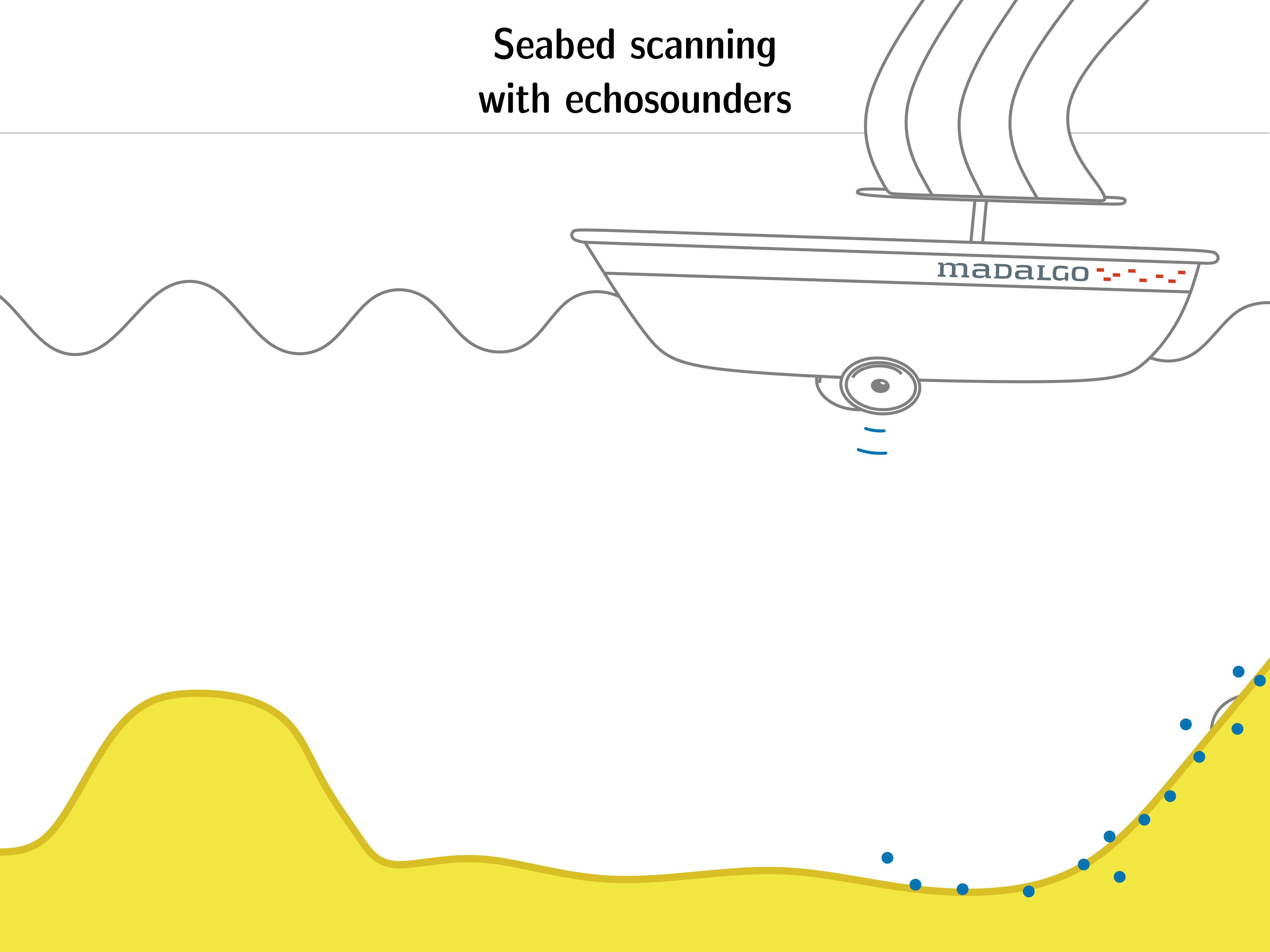

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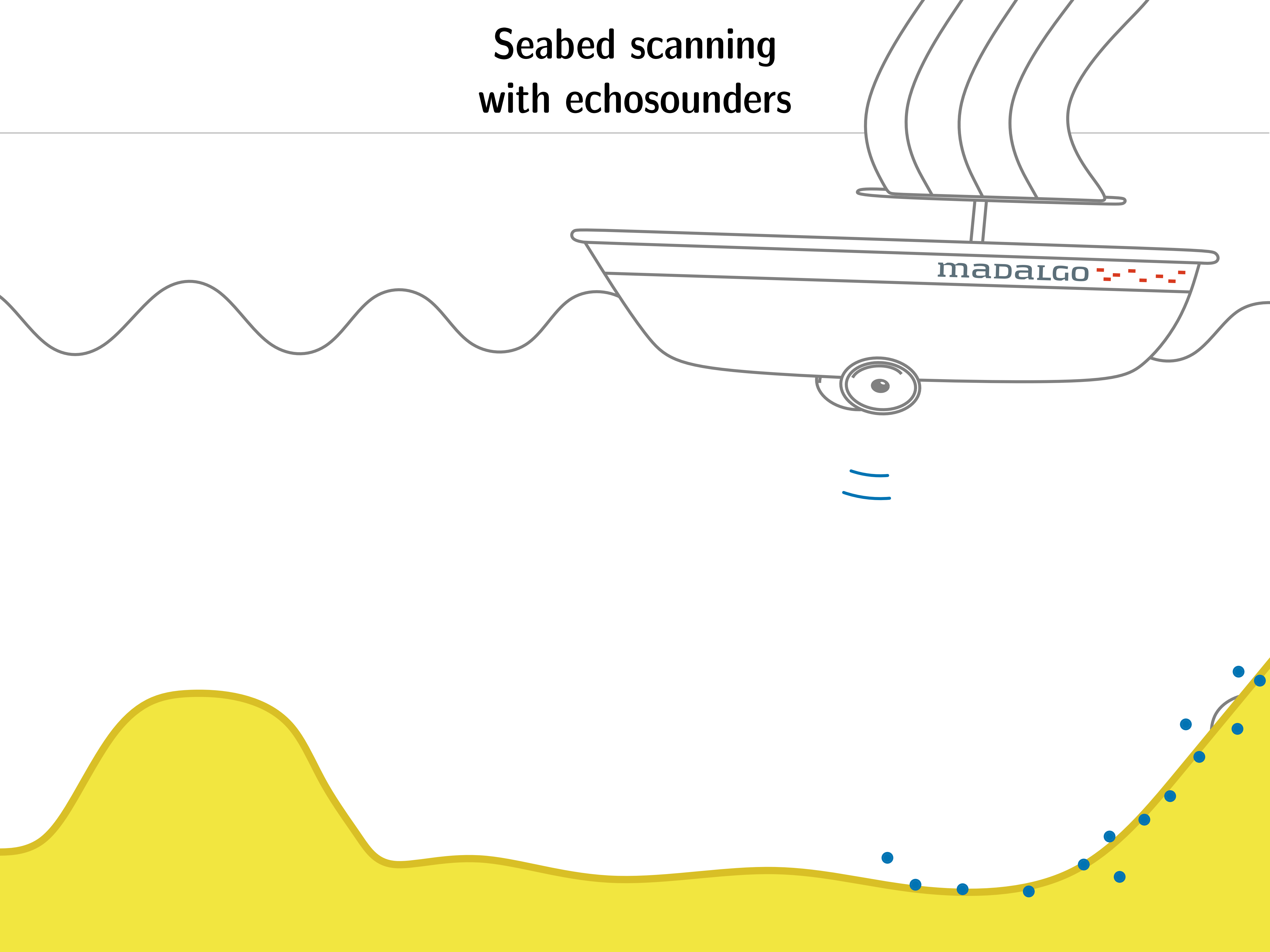

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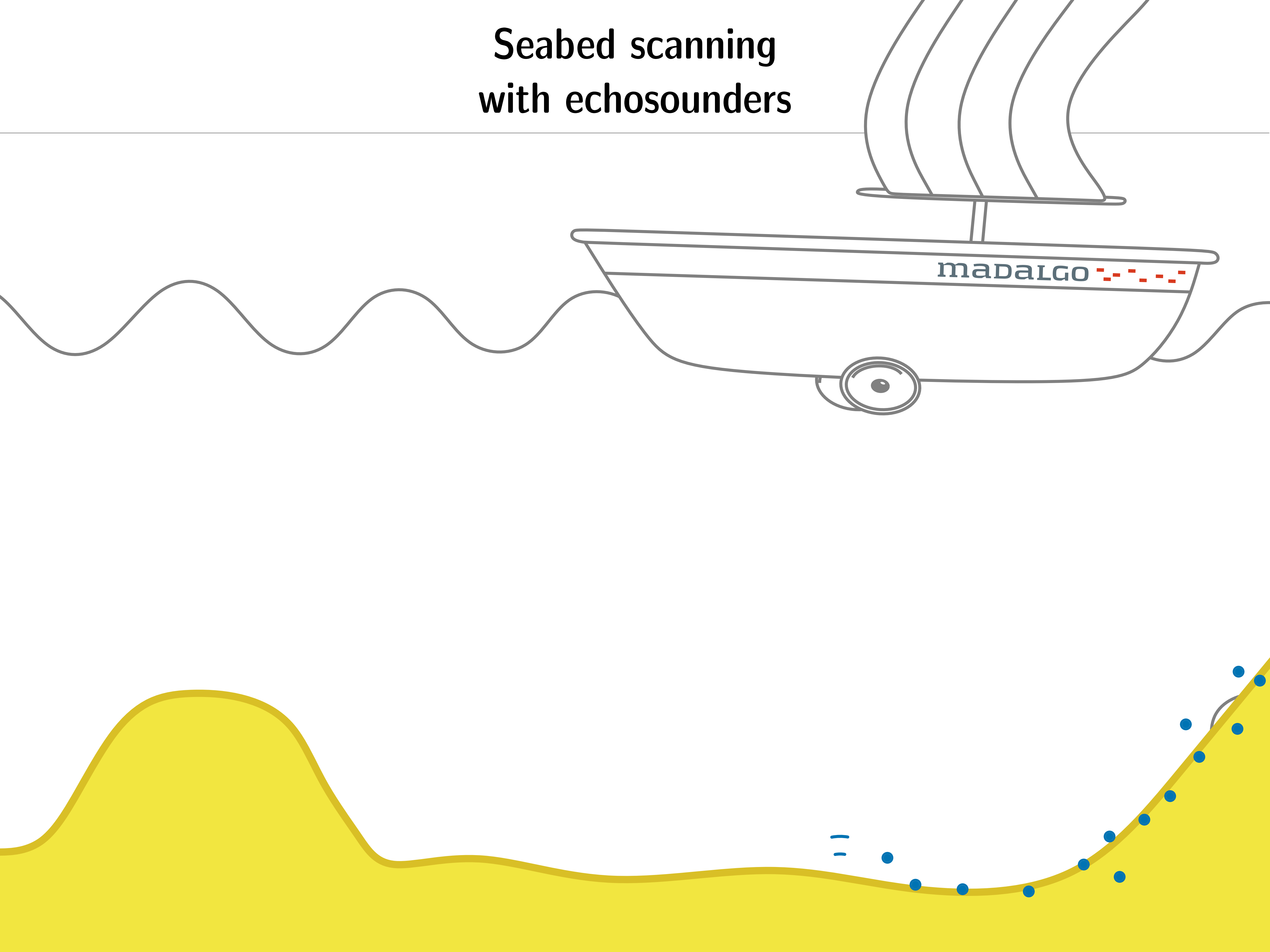

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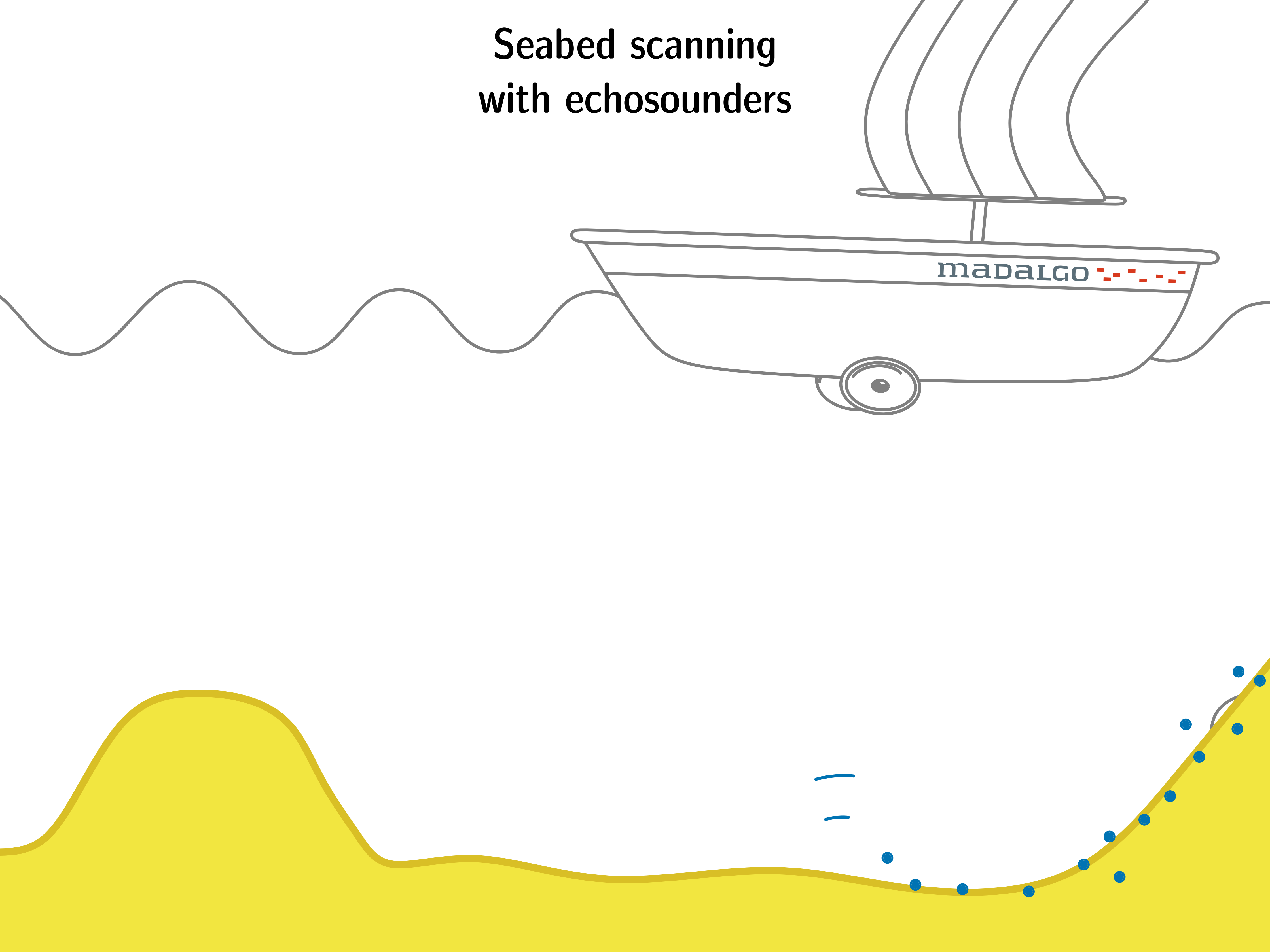

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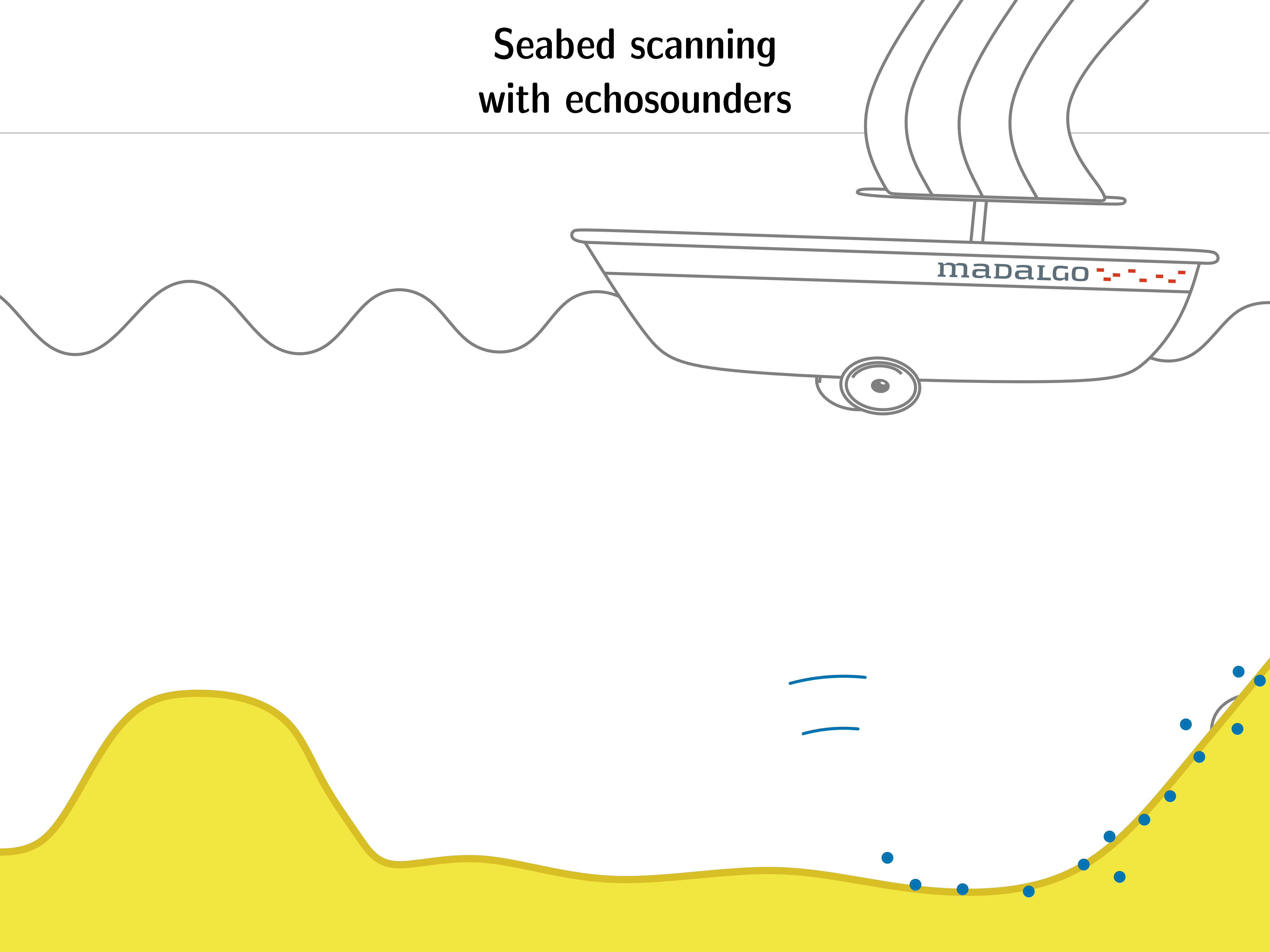

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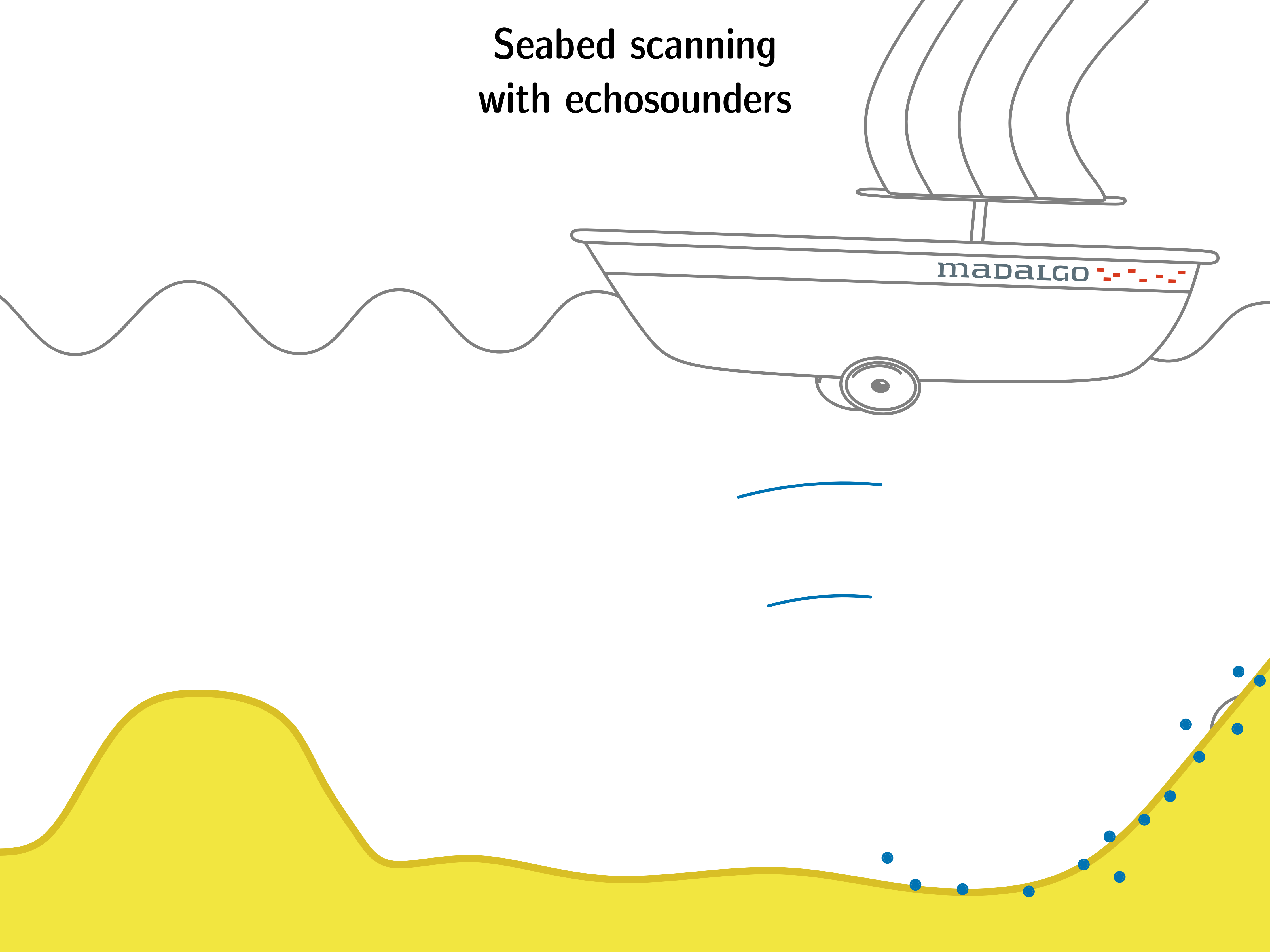

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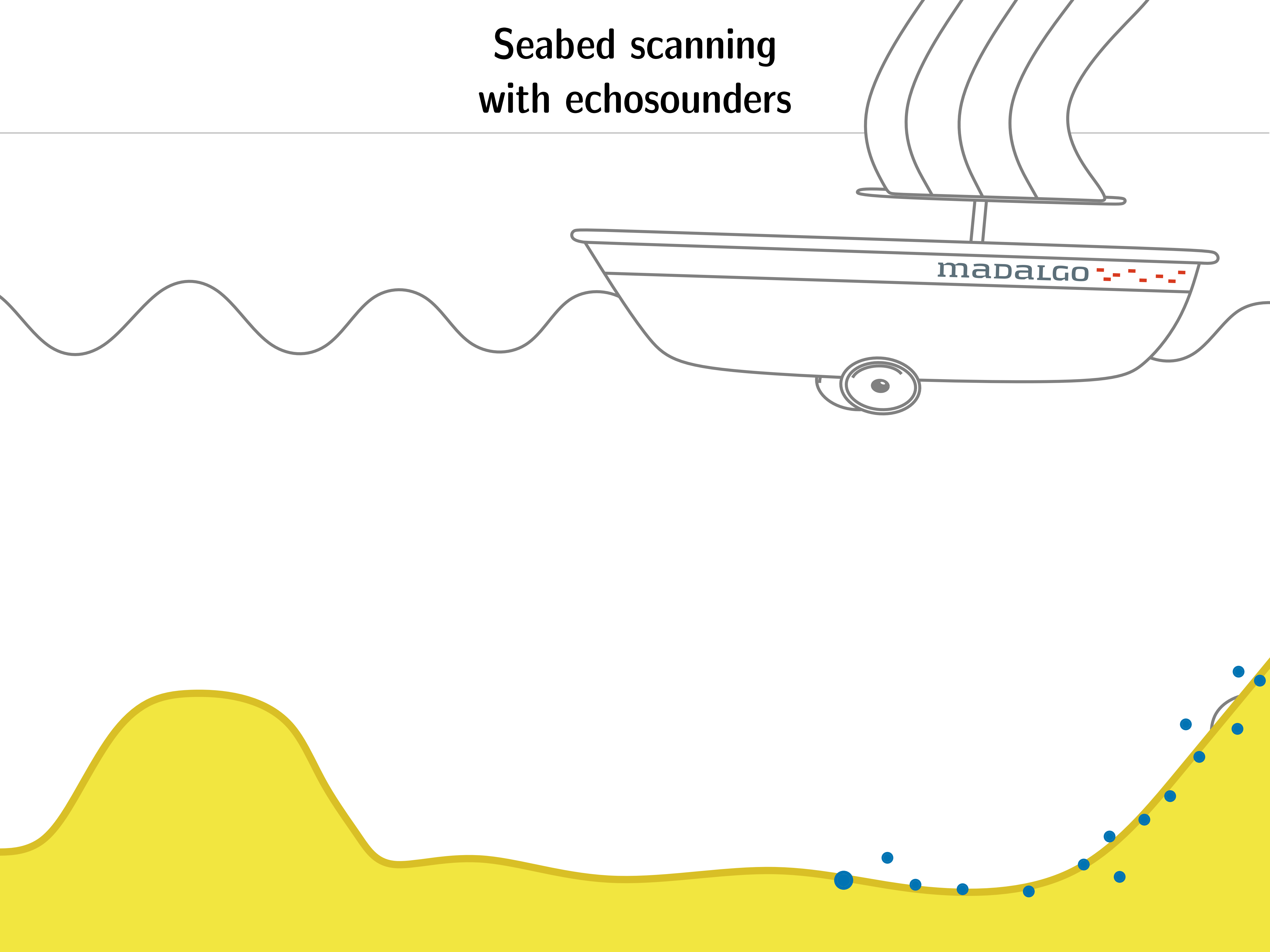

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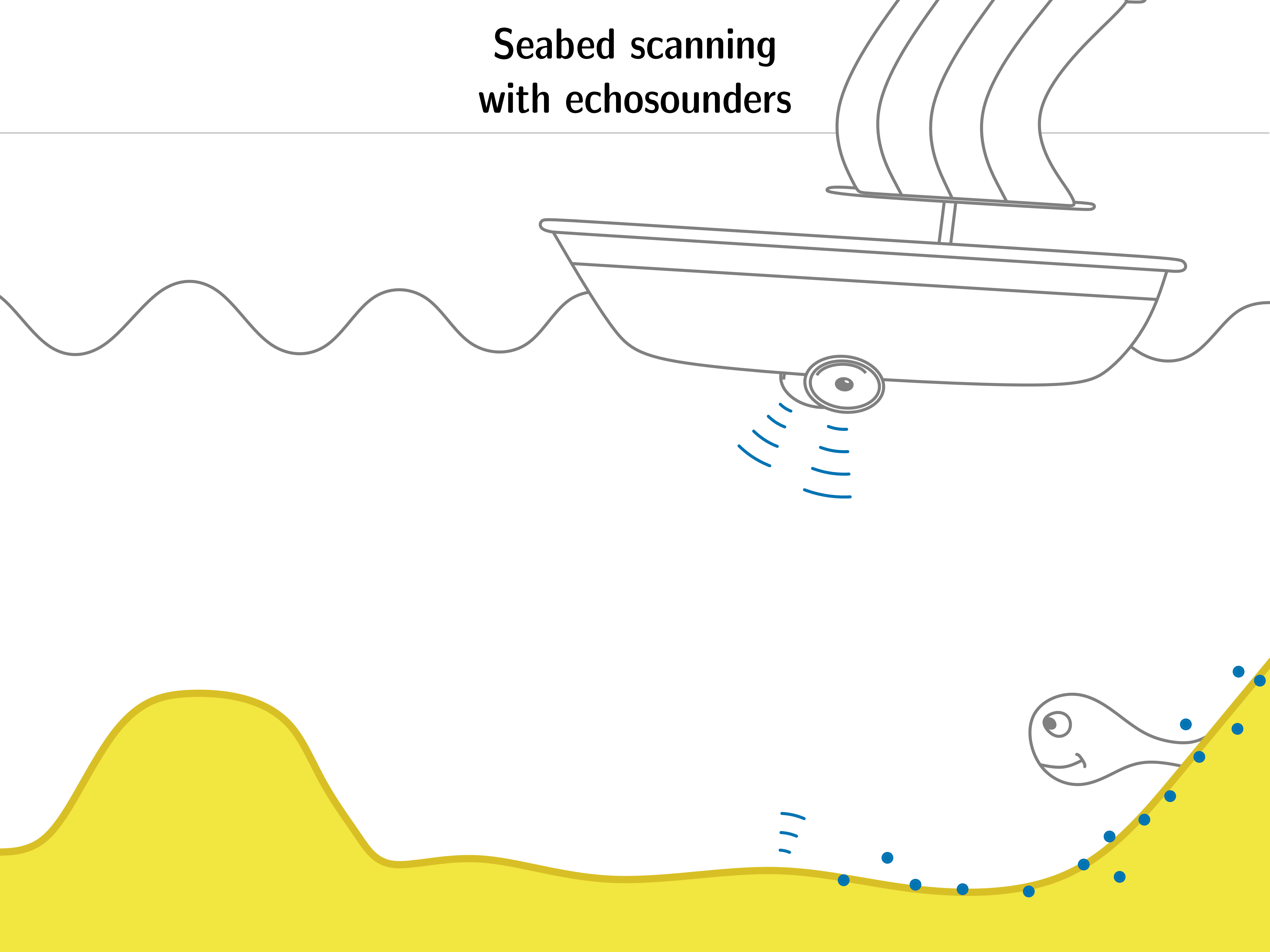

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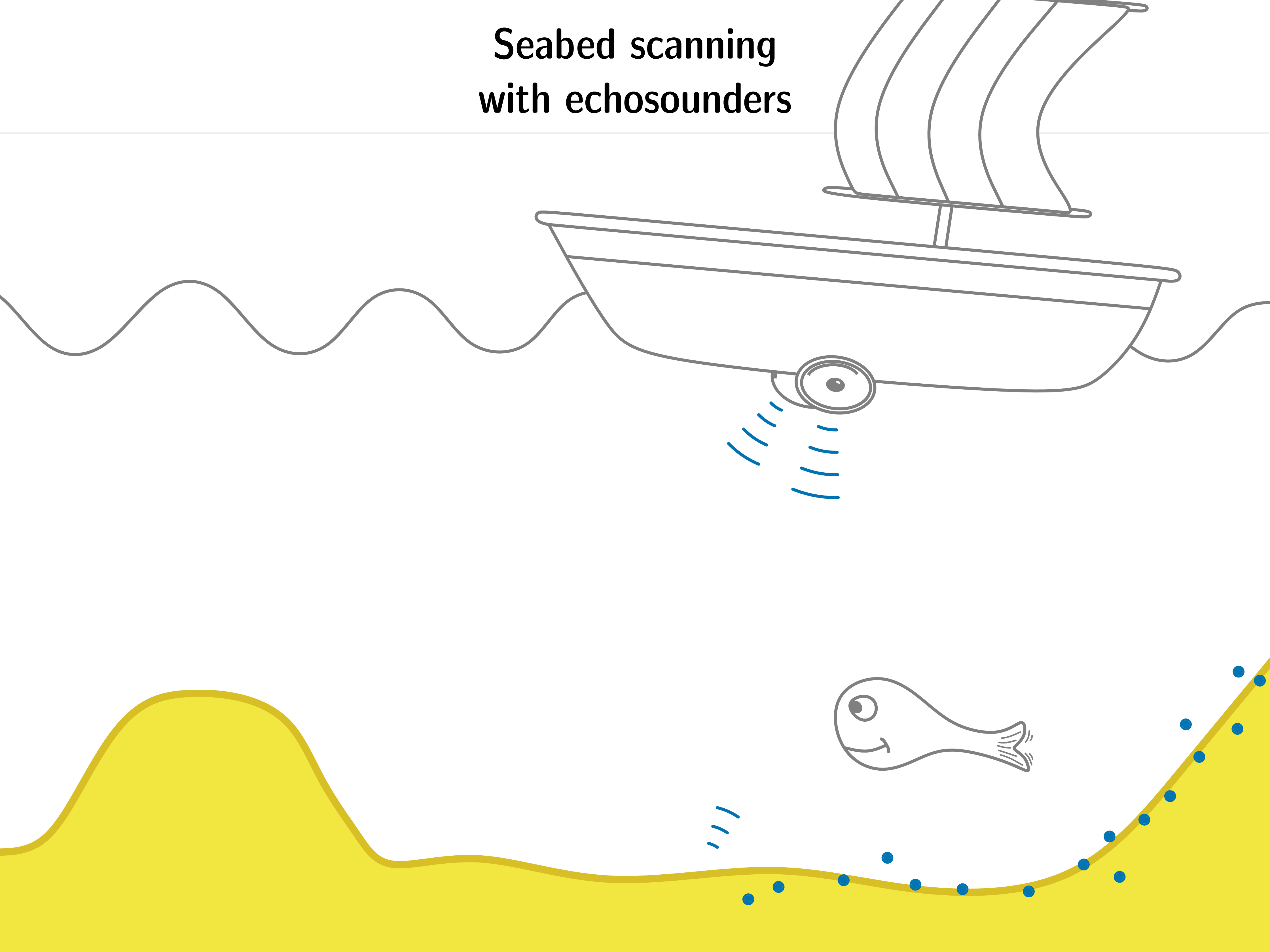

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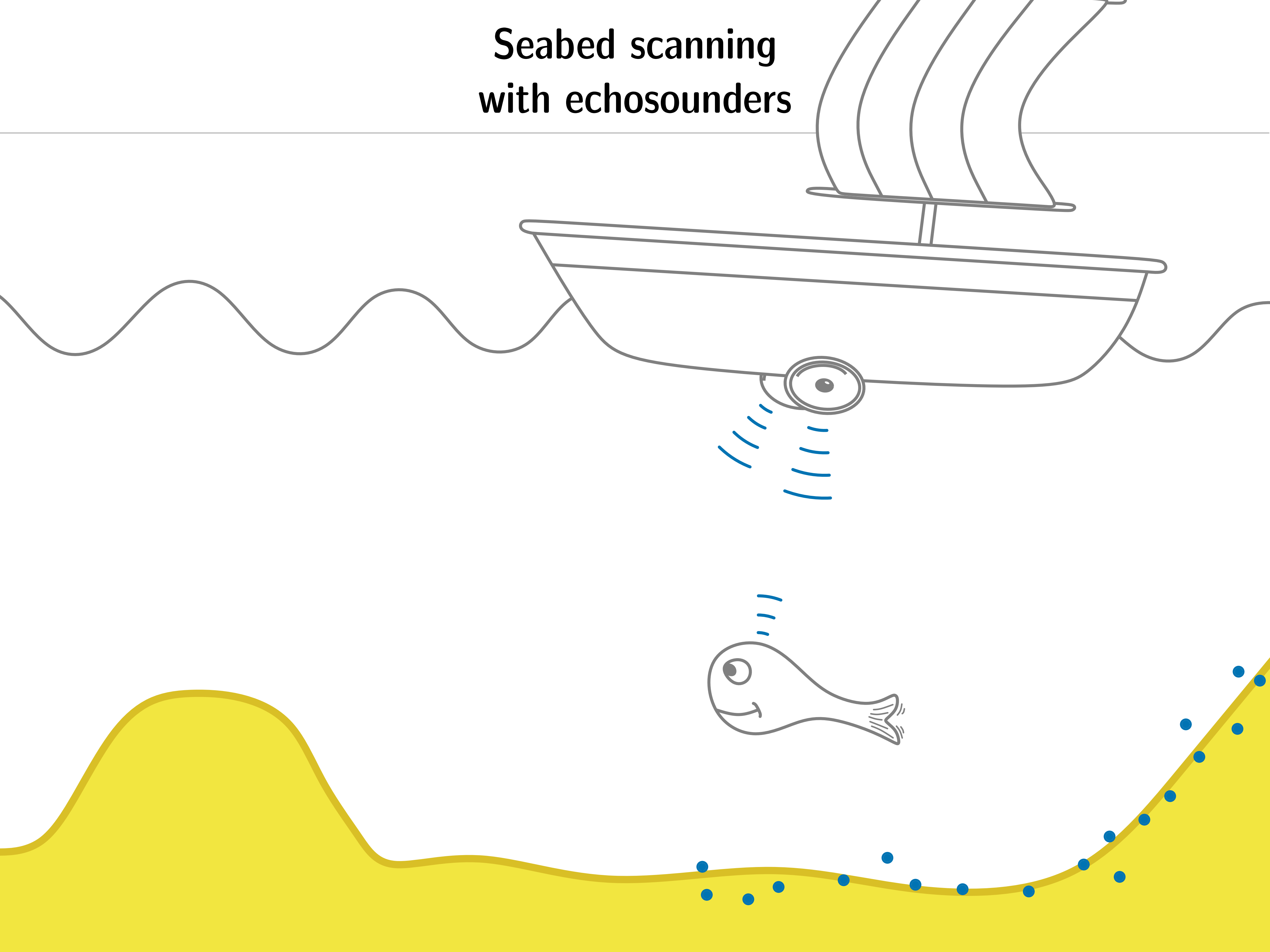

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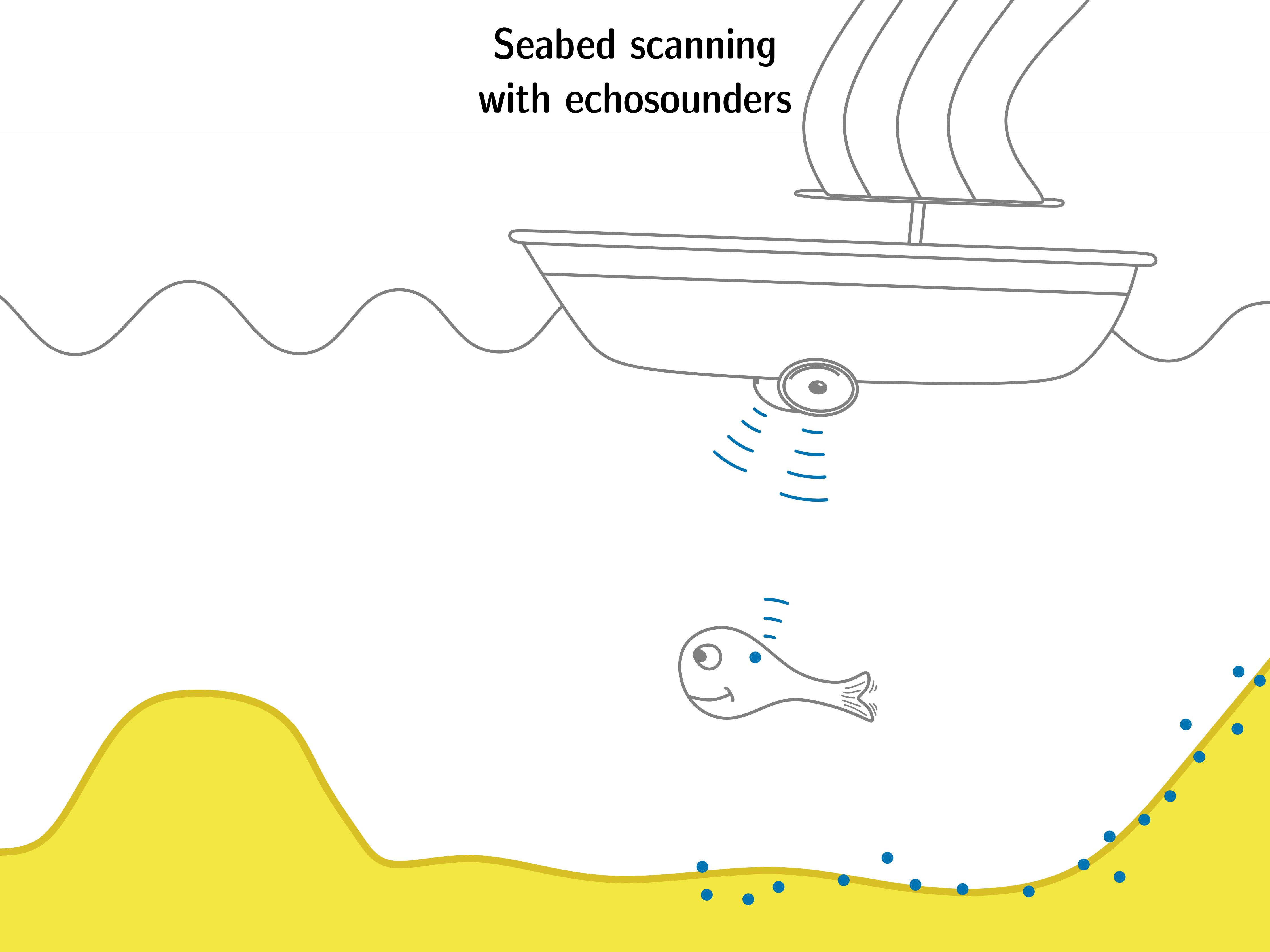

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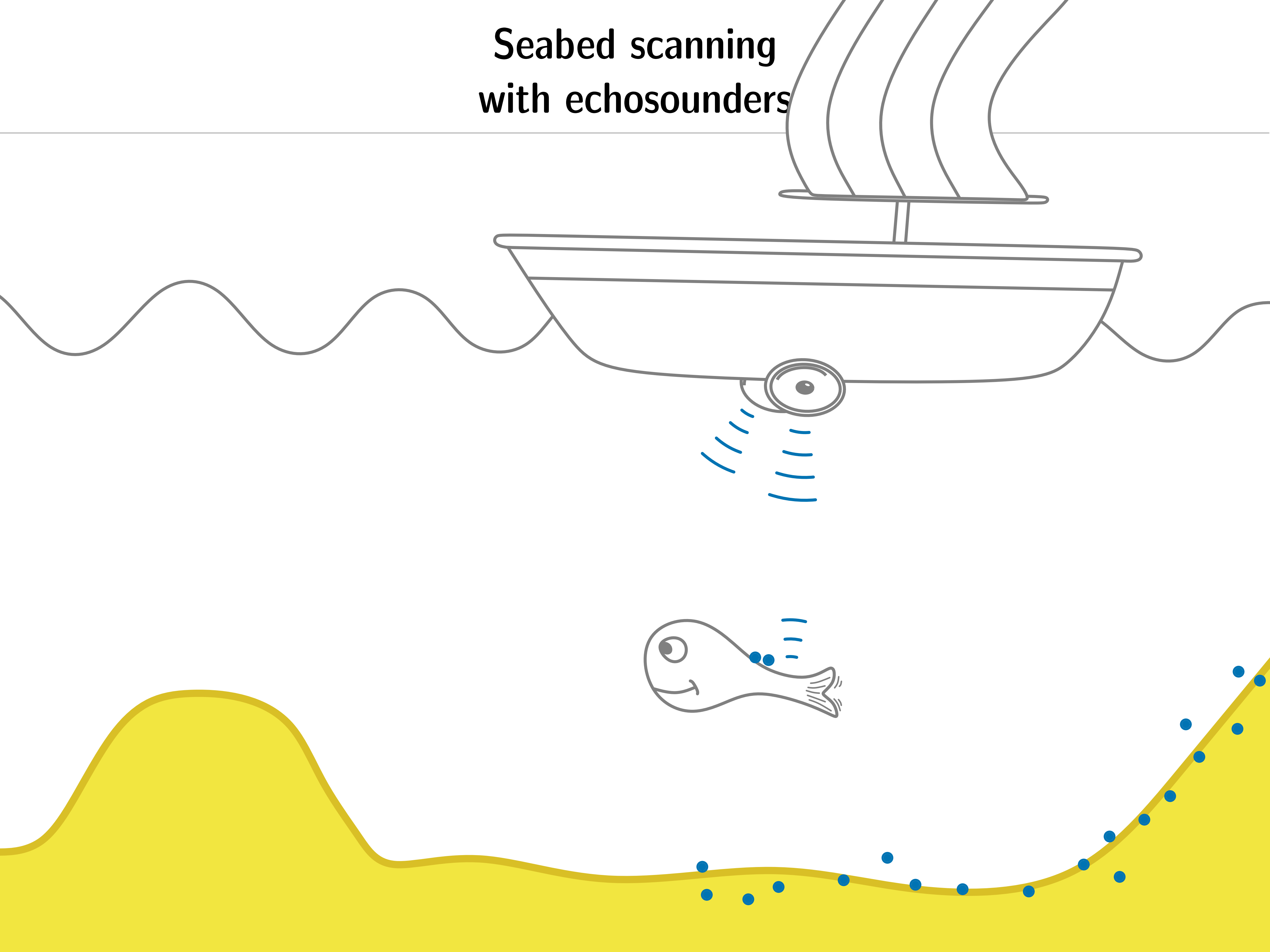

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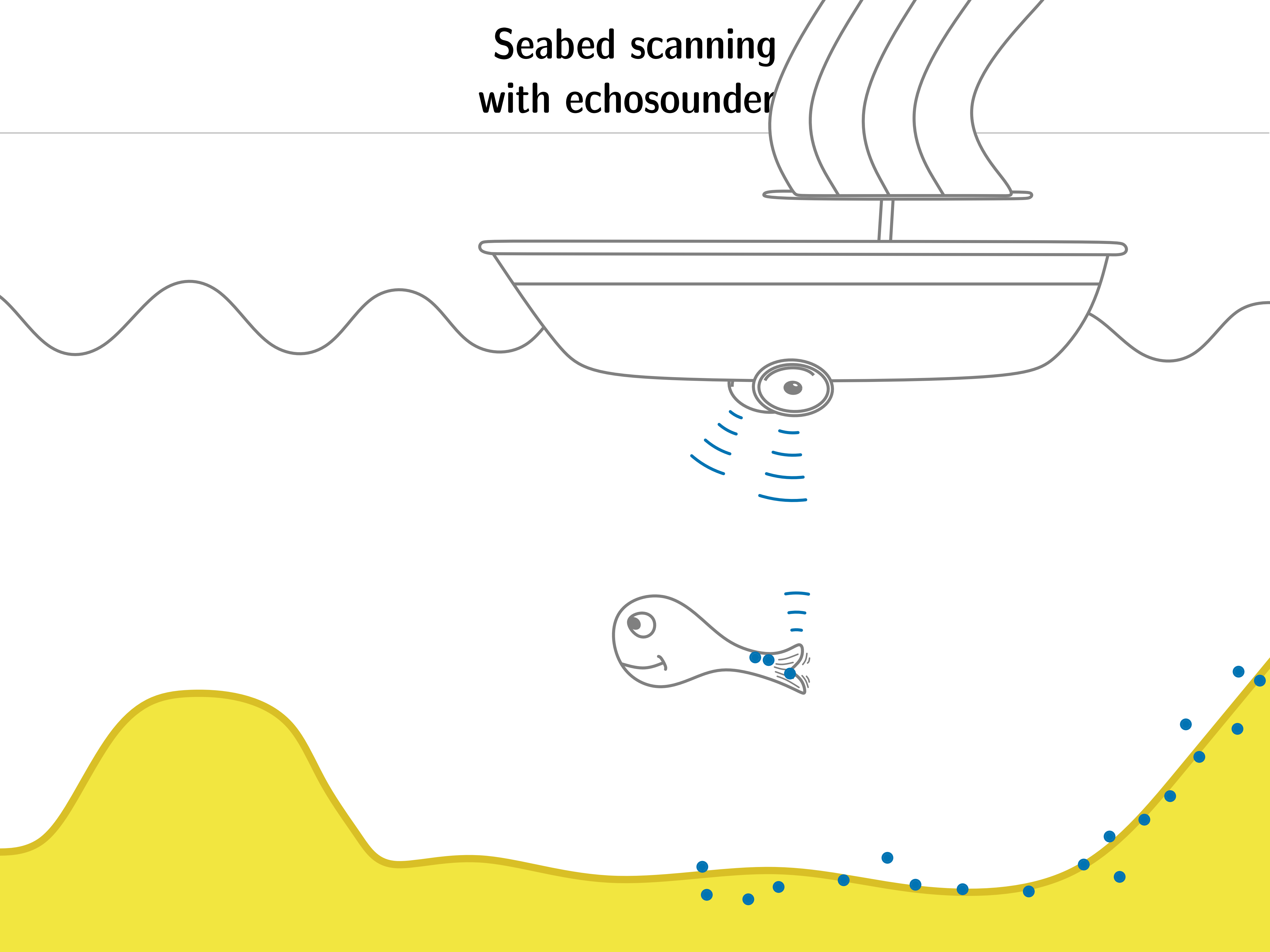

Seabed scanning
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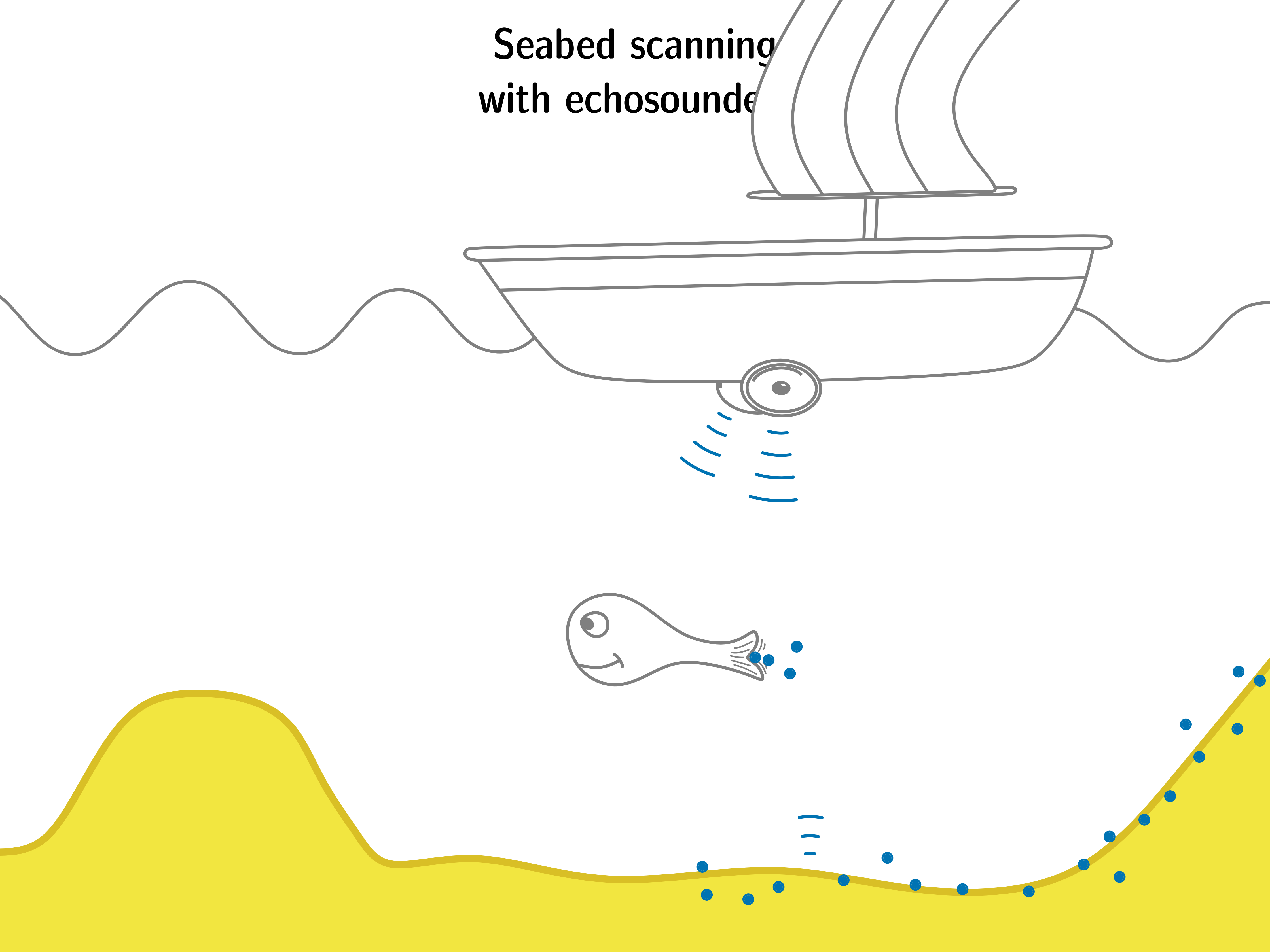

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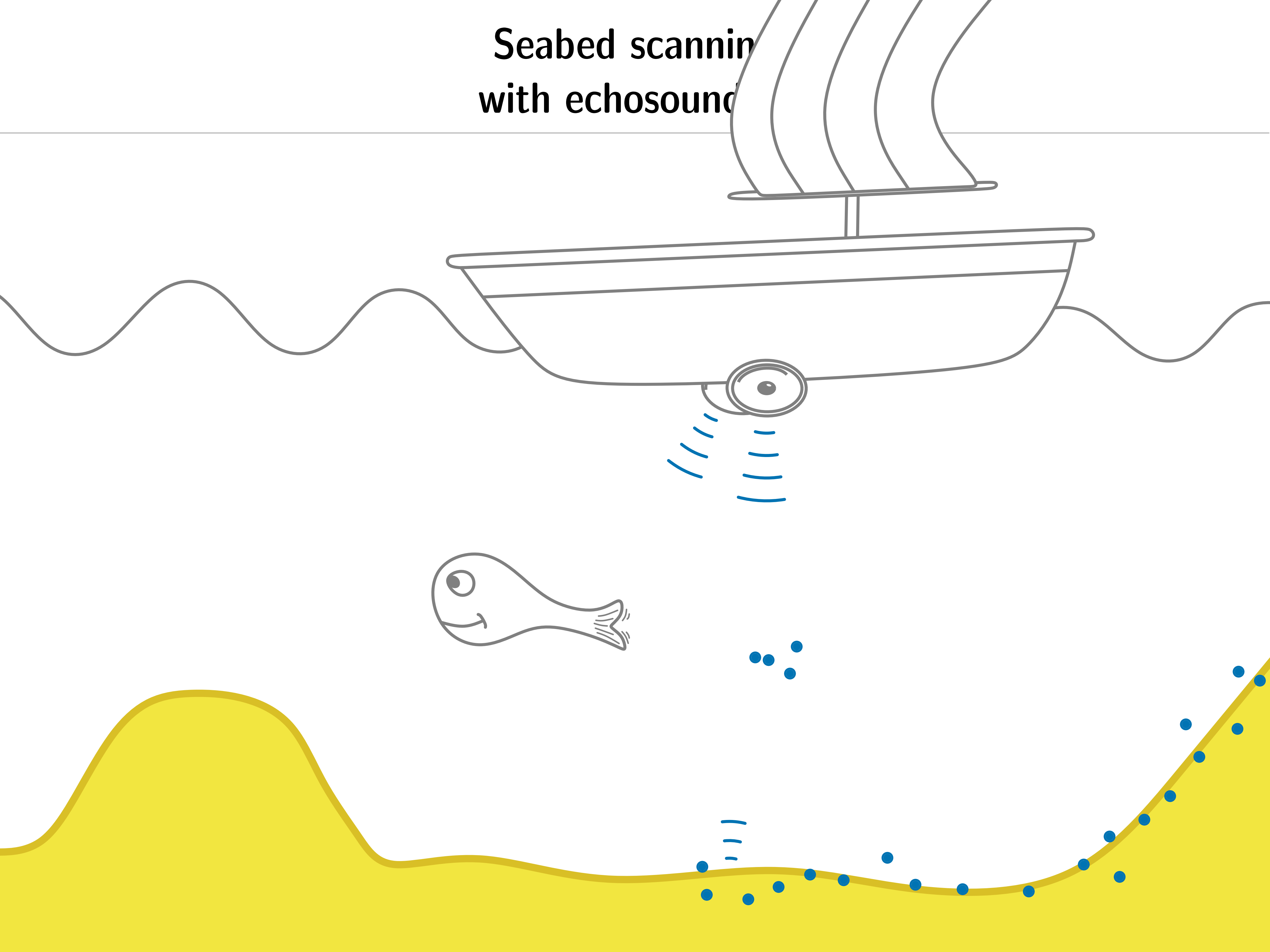
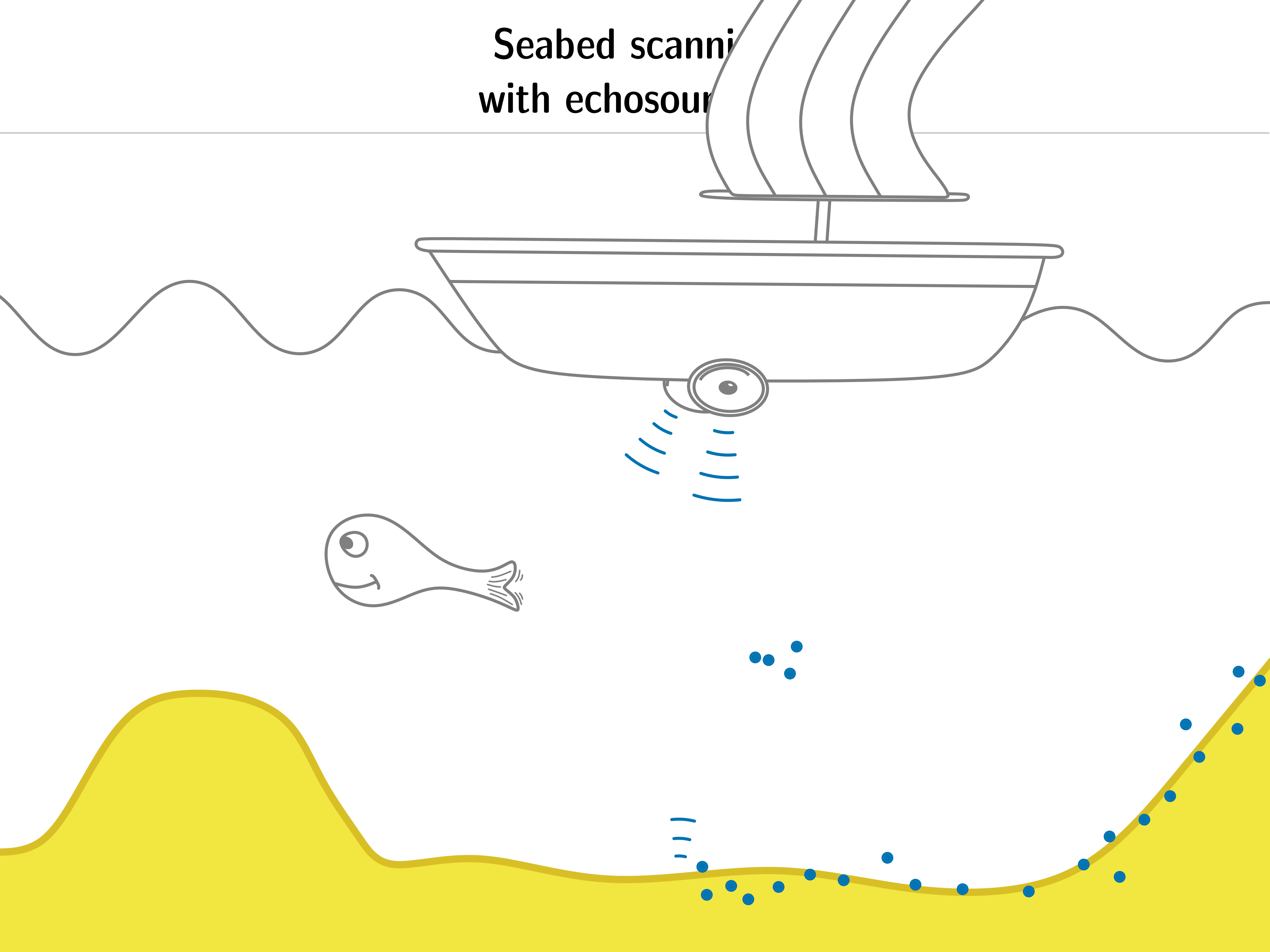


Seabed scanni with echosour



Seabed sca
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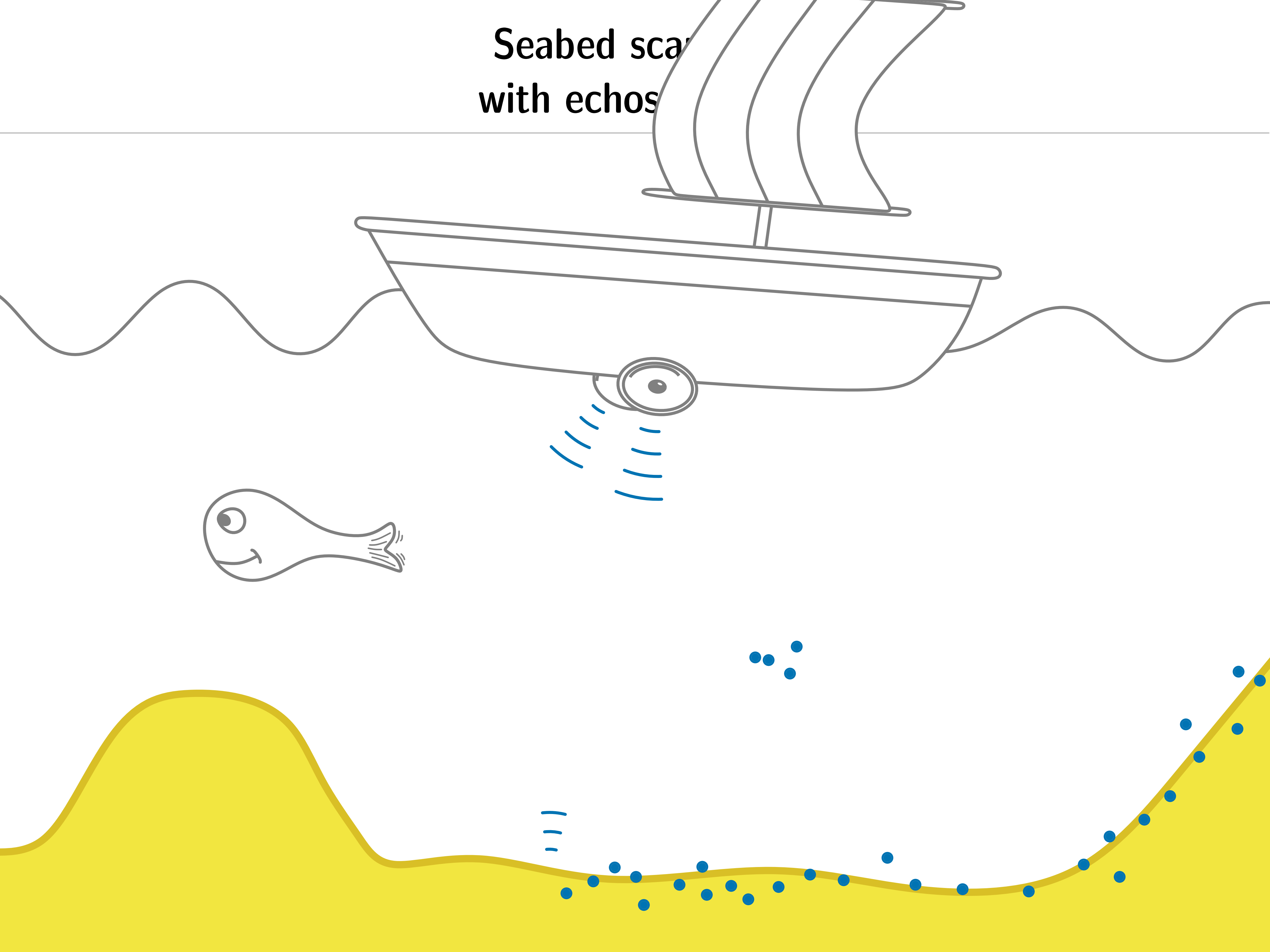

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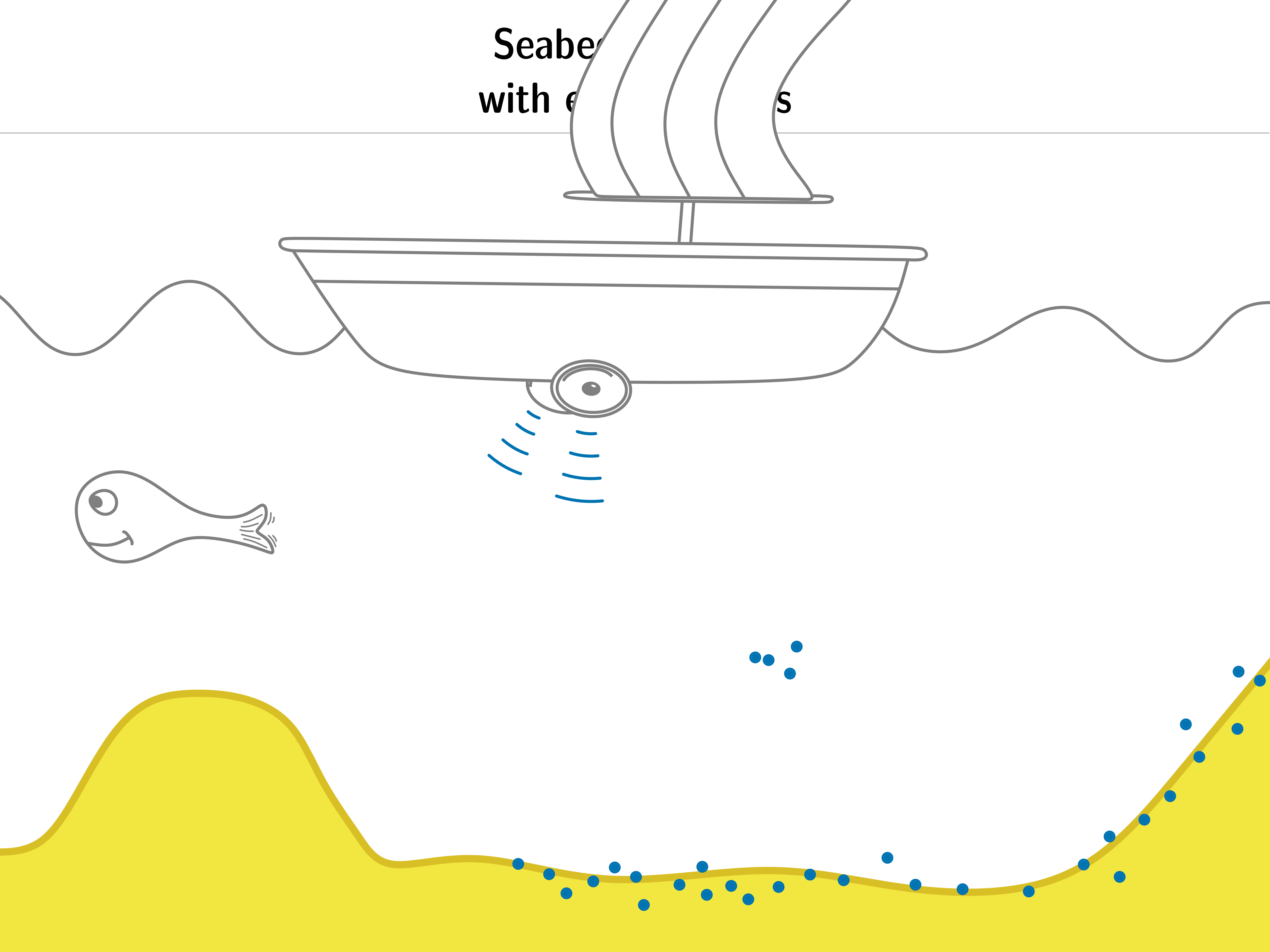

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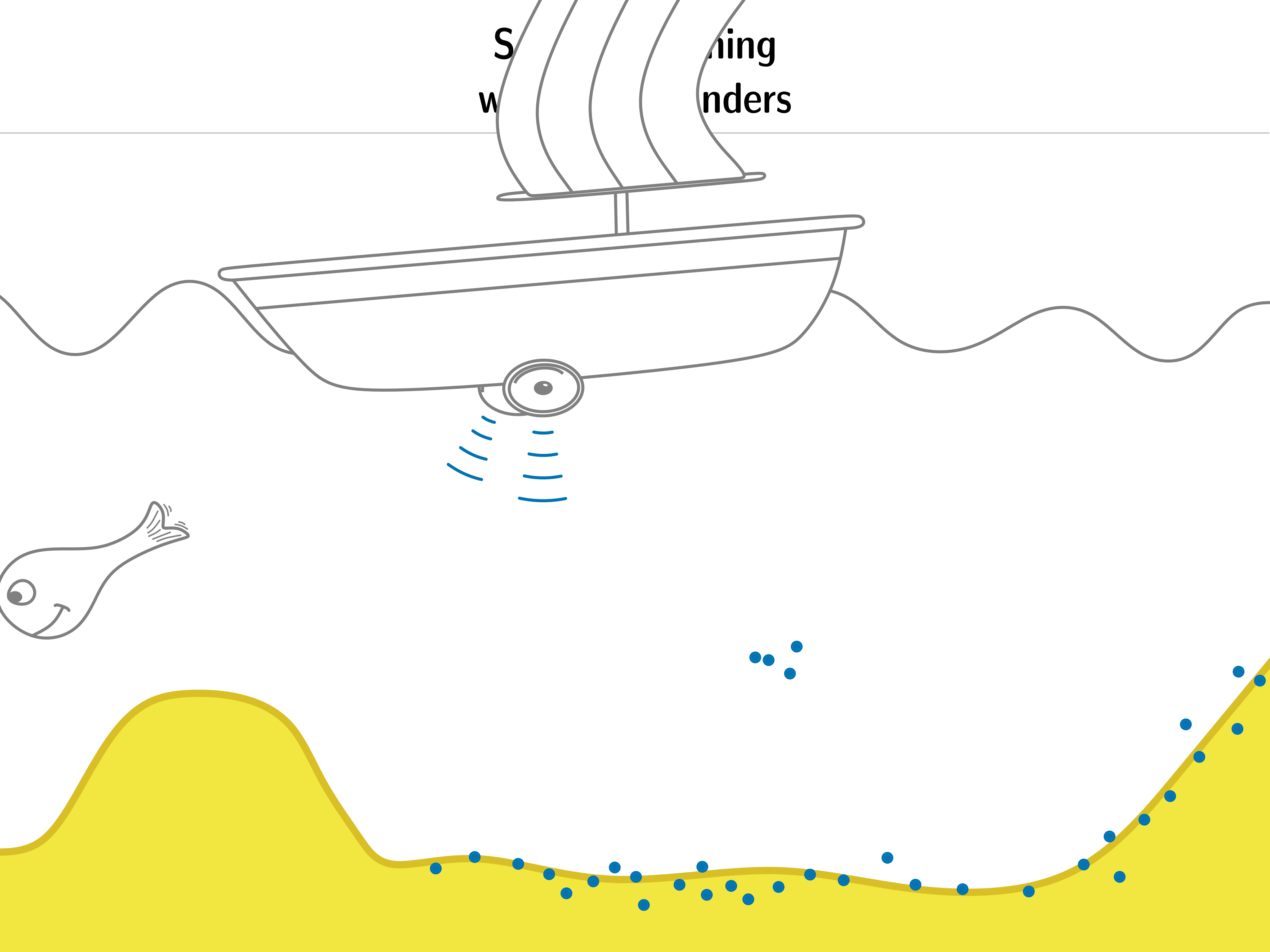

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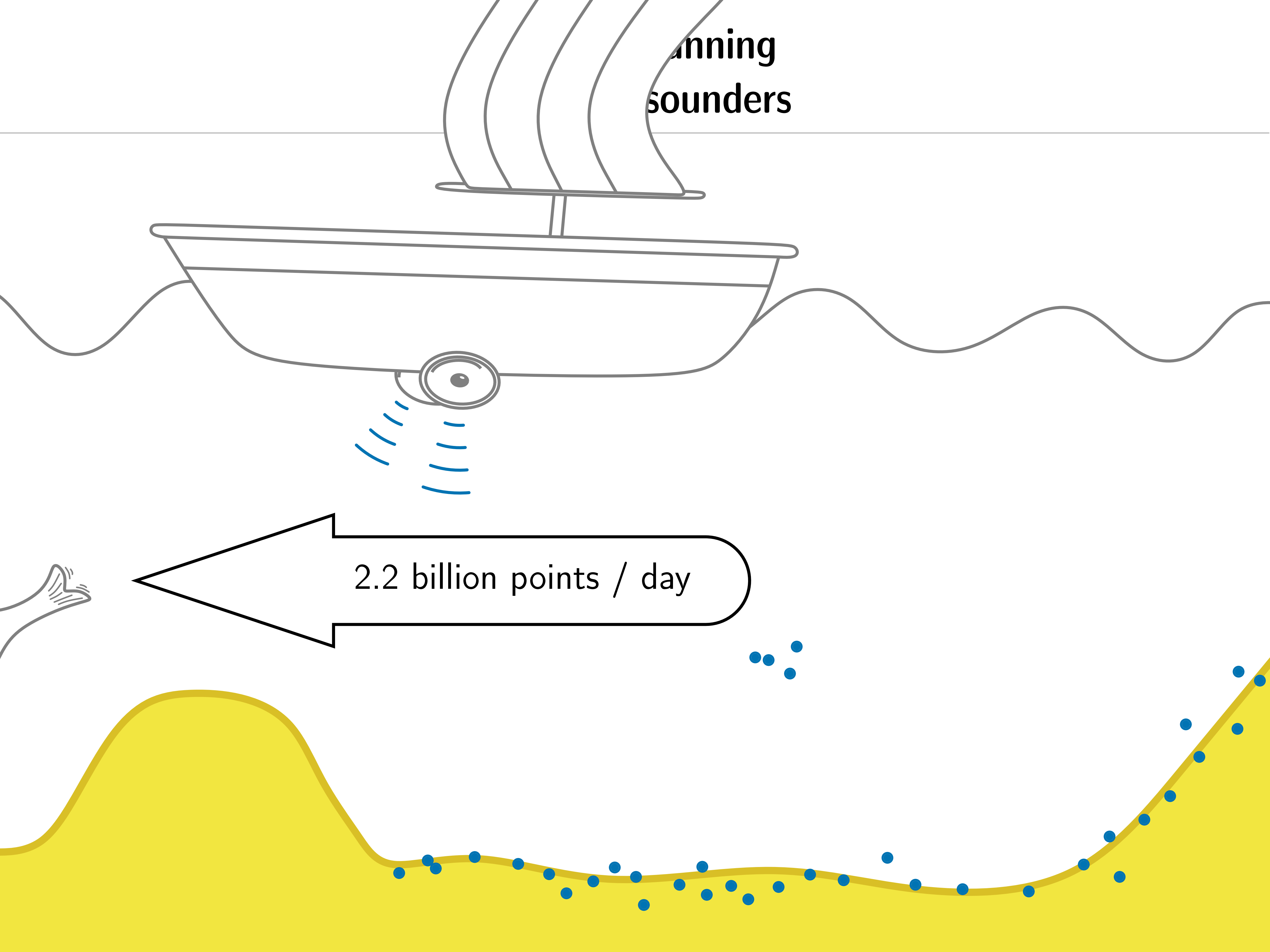

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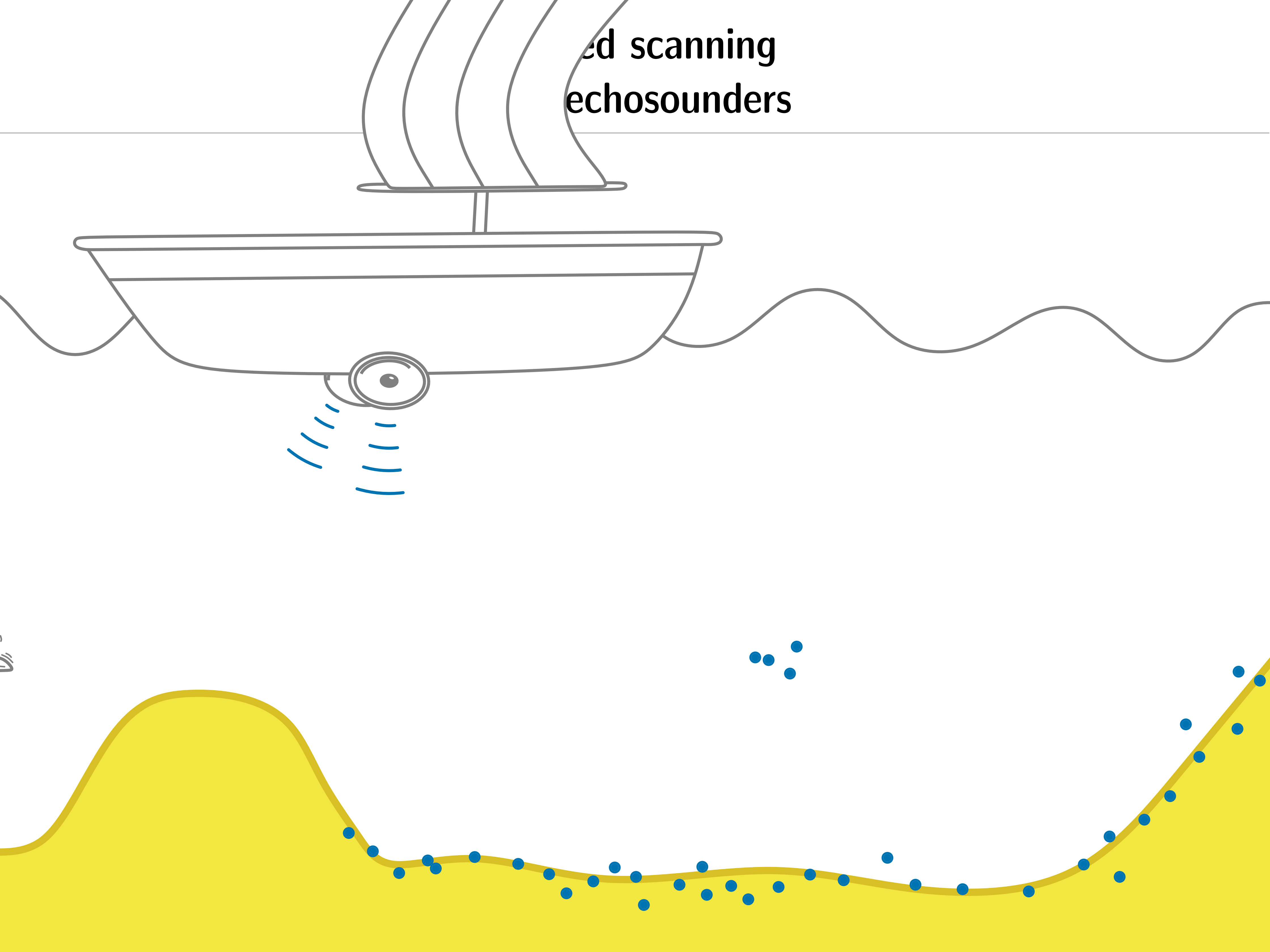
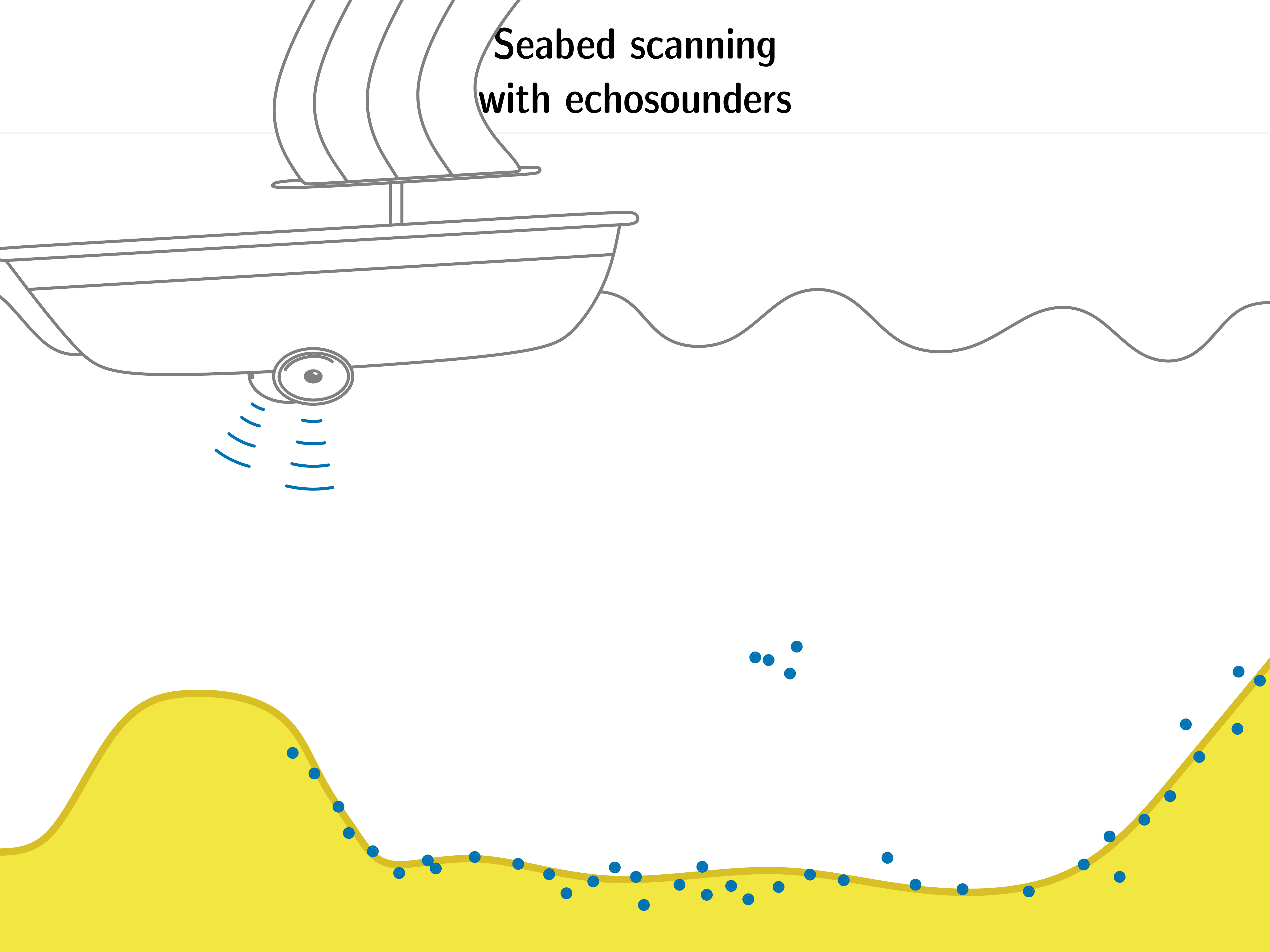


Seabed scanning with echosounders



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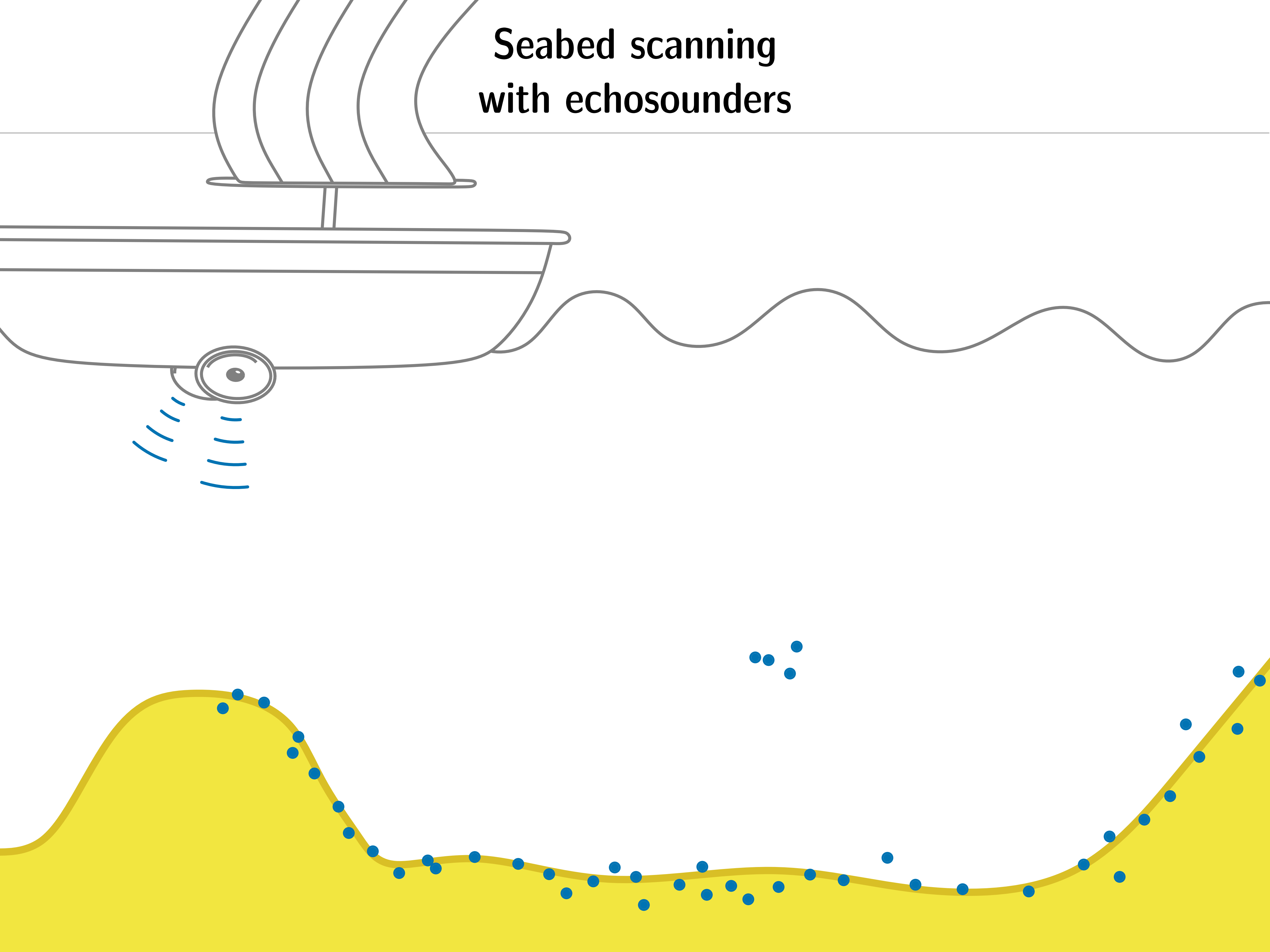

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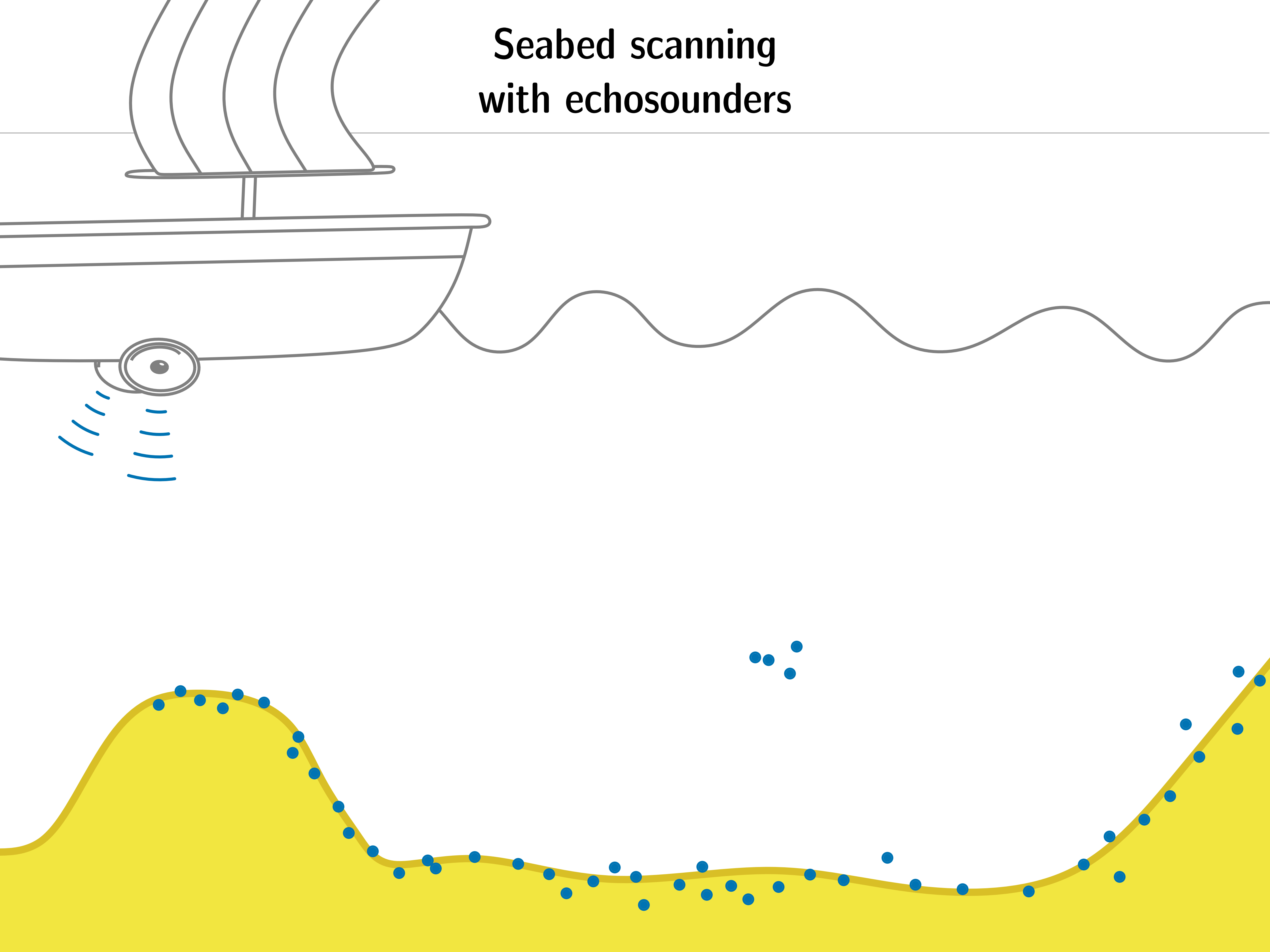

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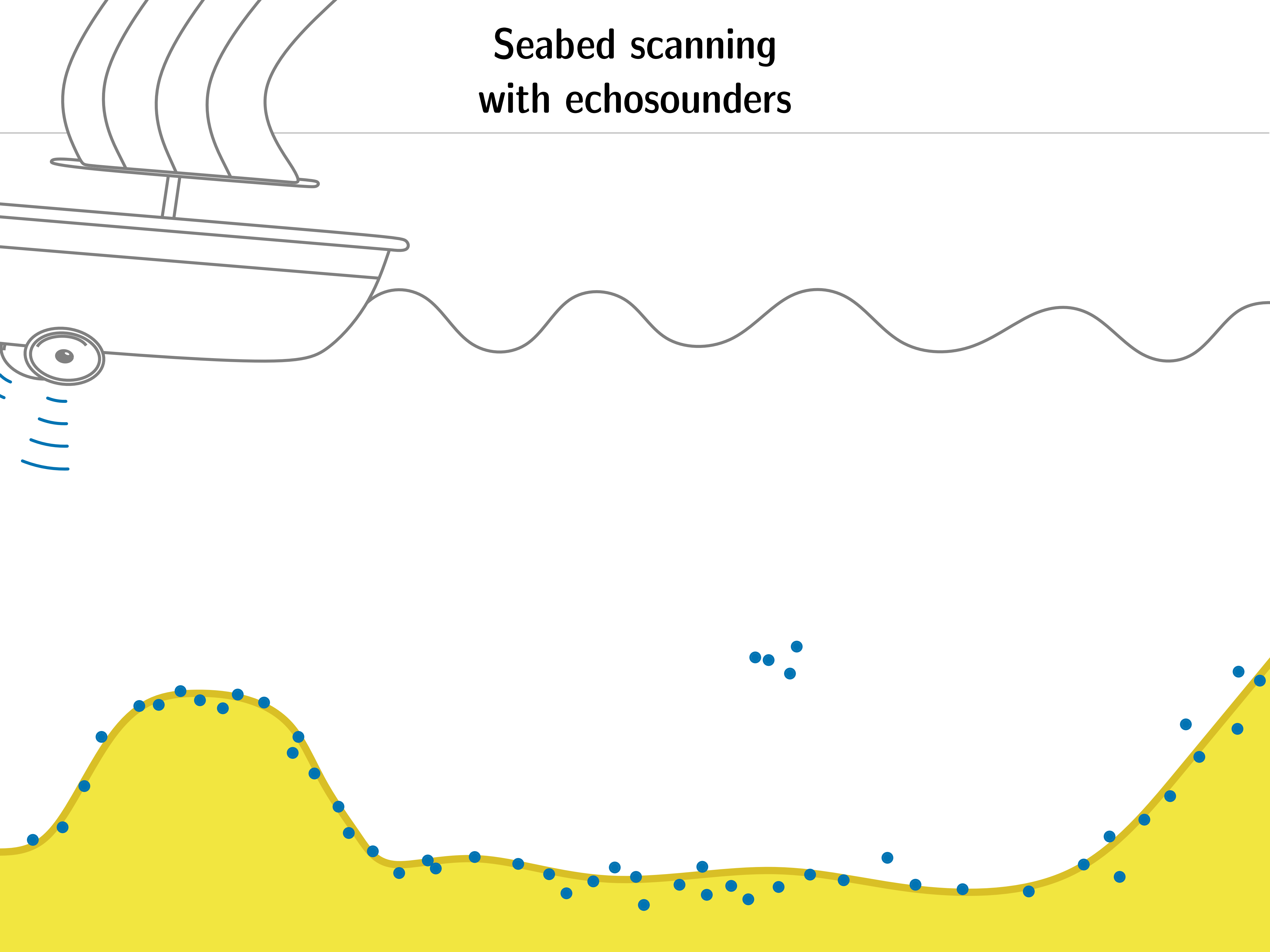

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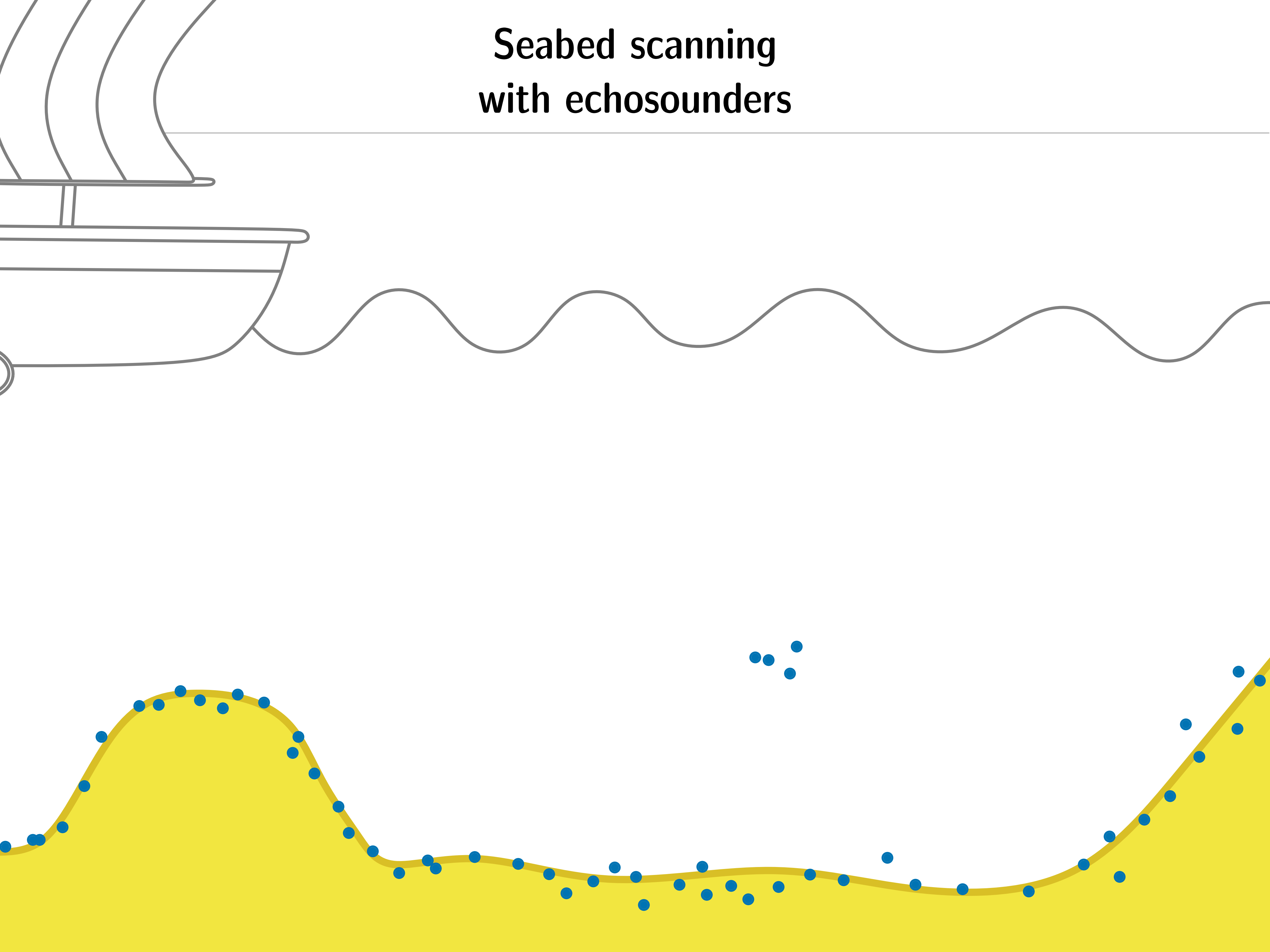
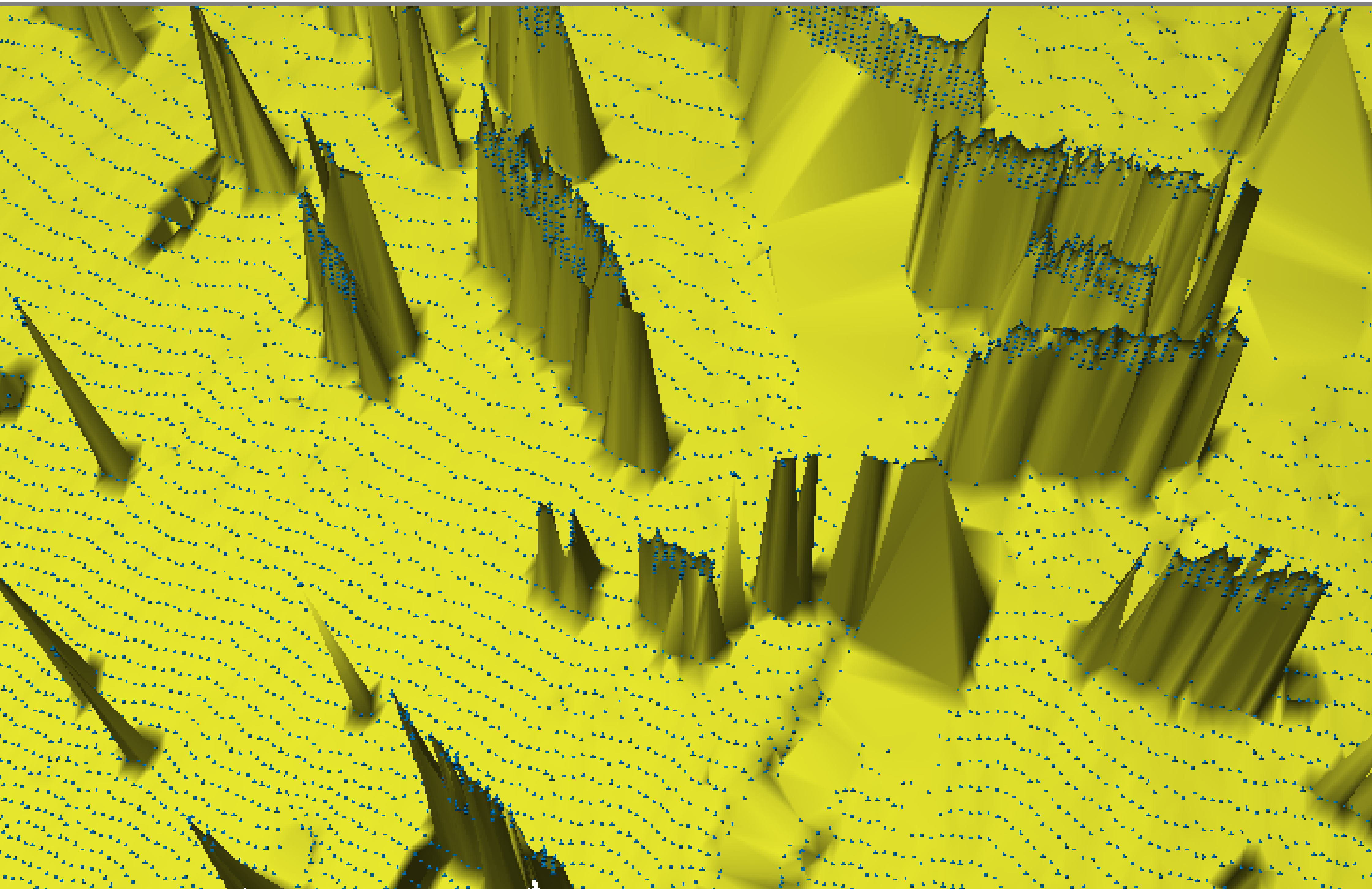


Real-world examples

Data: StatoilHydro



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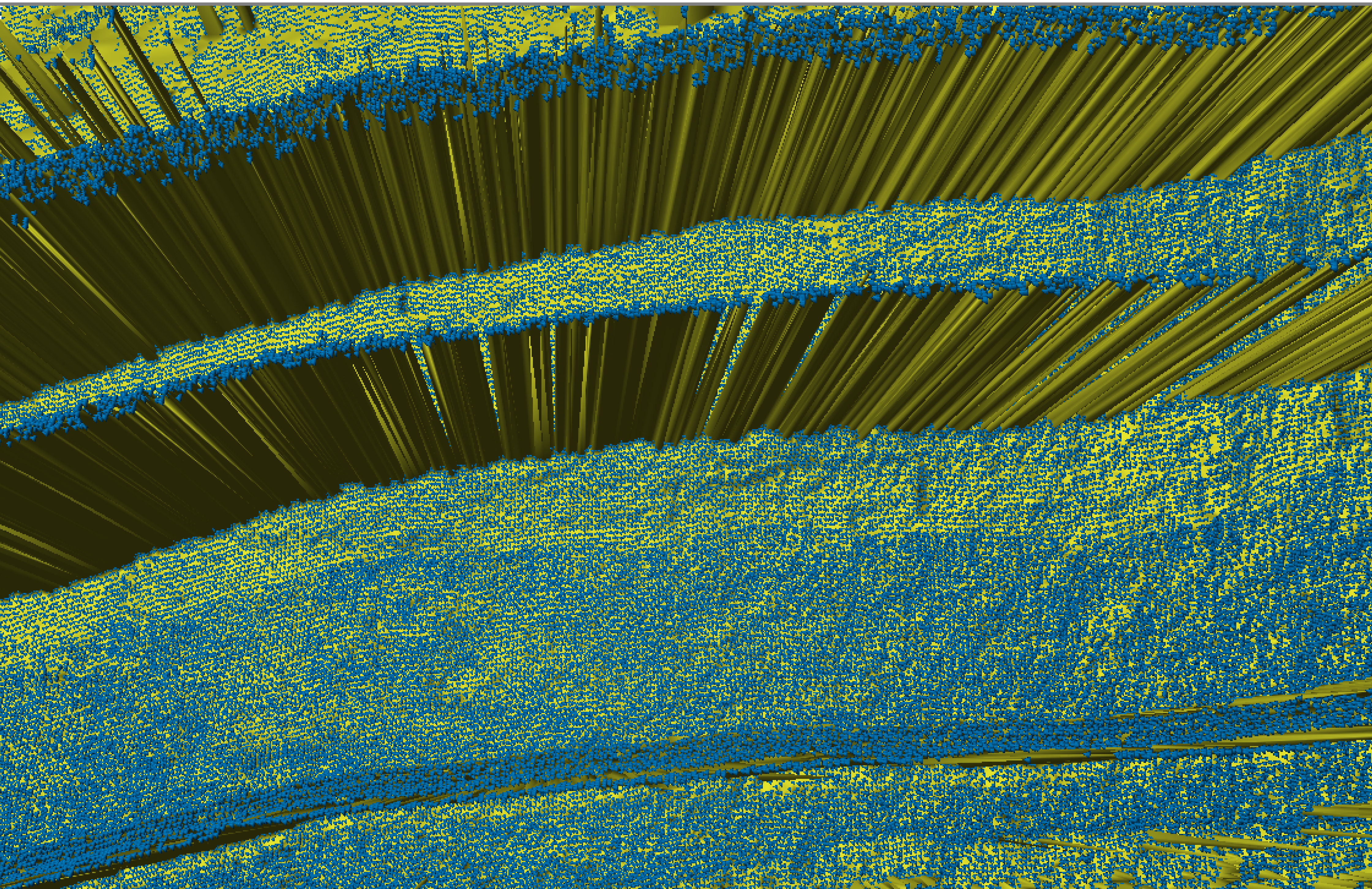

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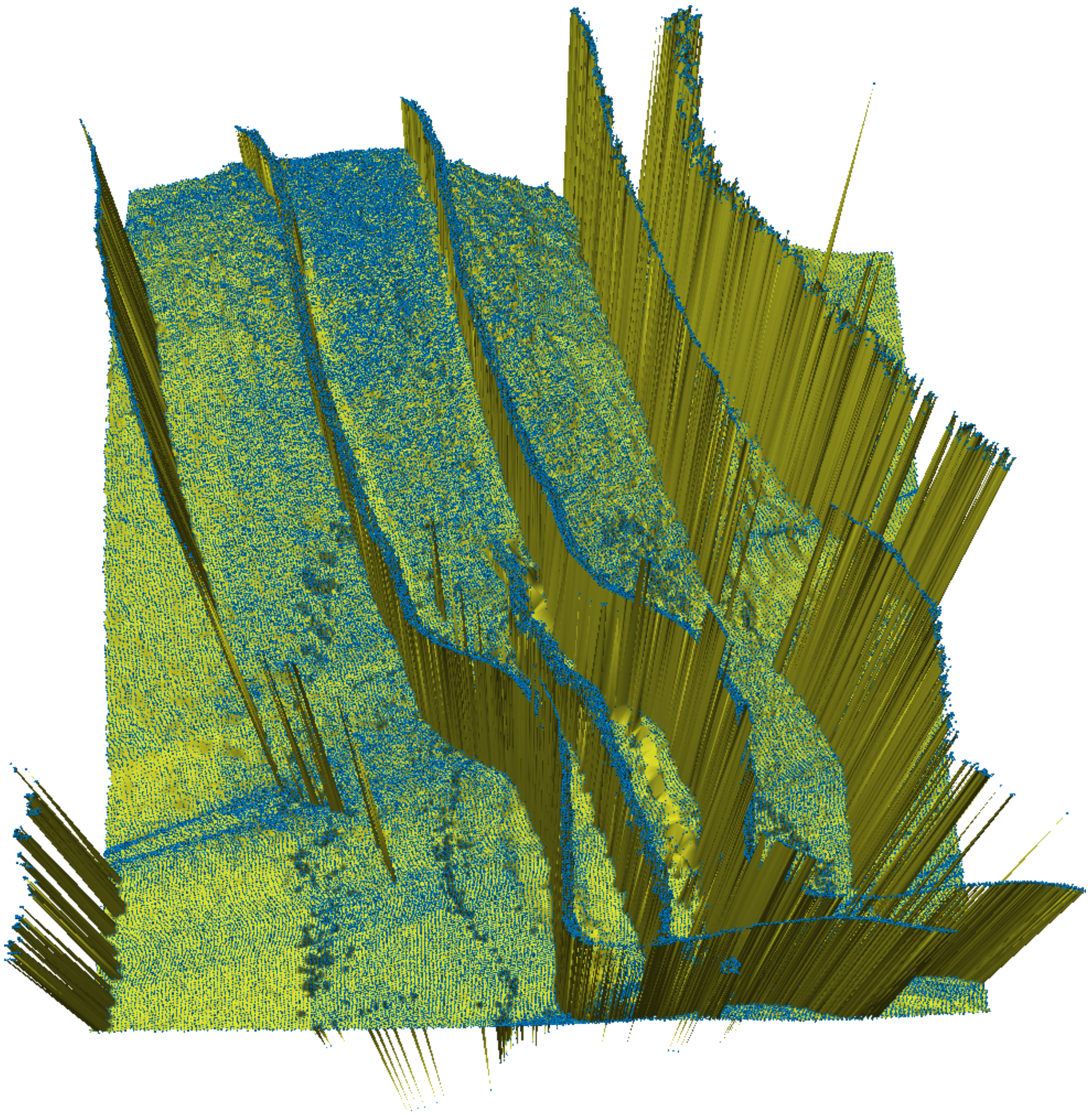

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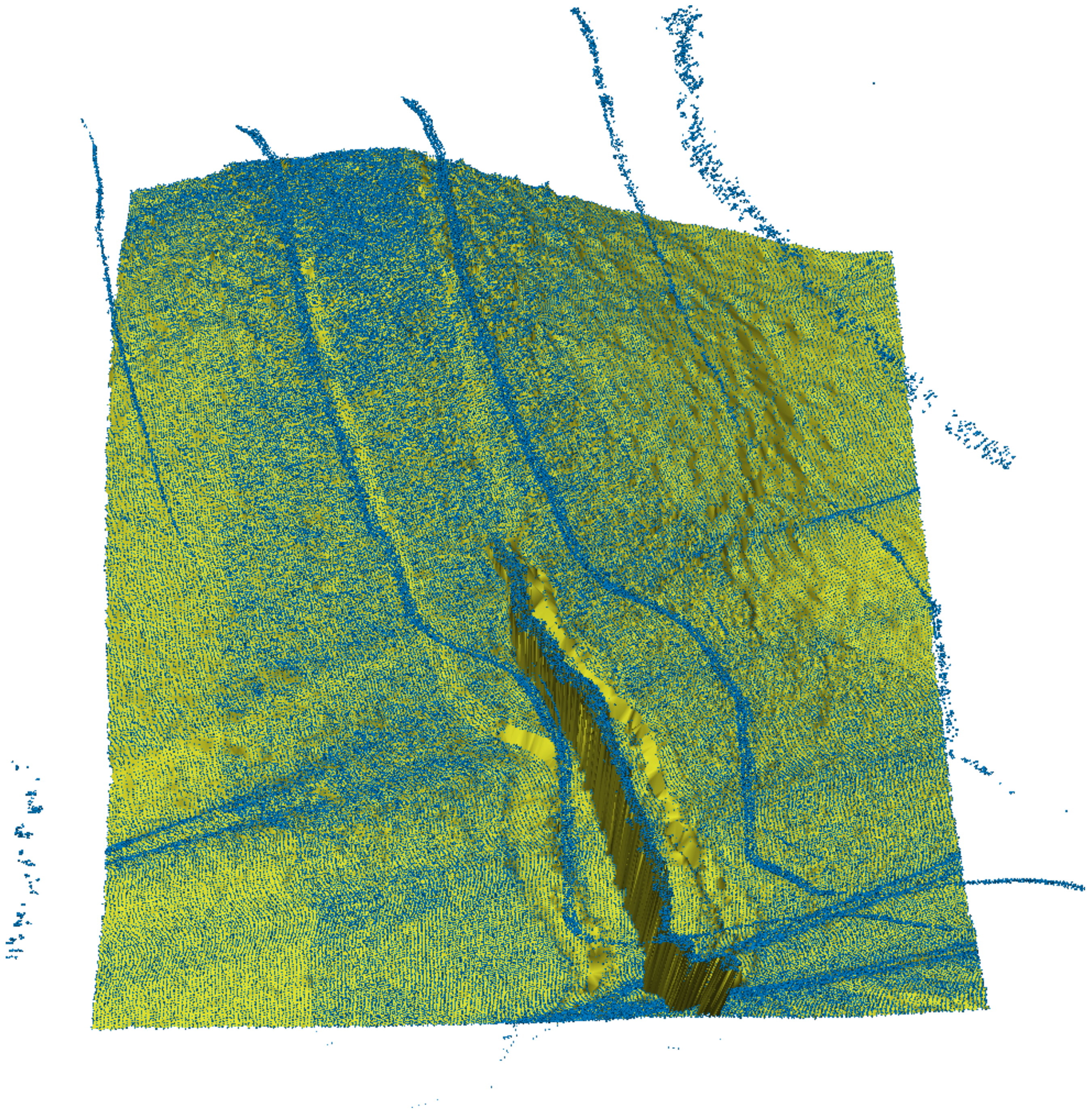
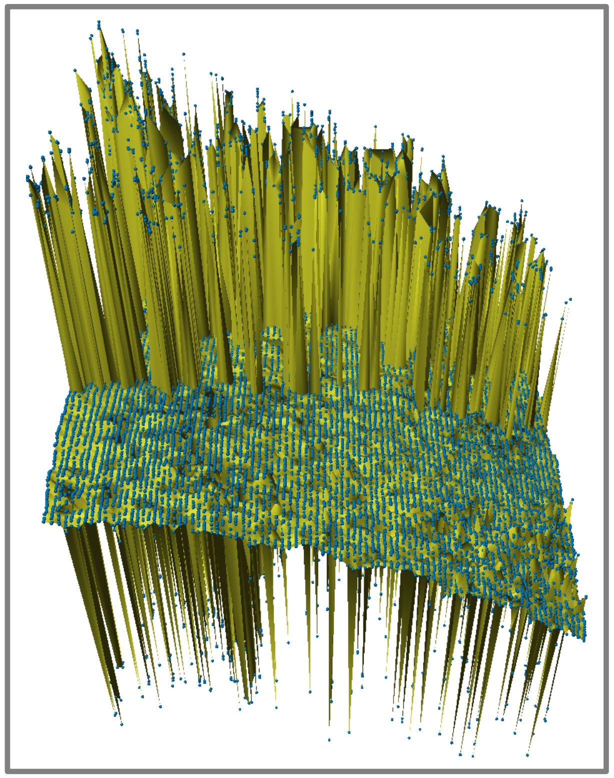


Noise types

Data: StatoilHydro

1. Random spikes, possibly clustered



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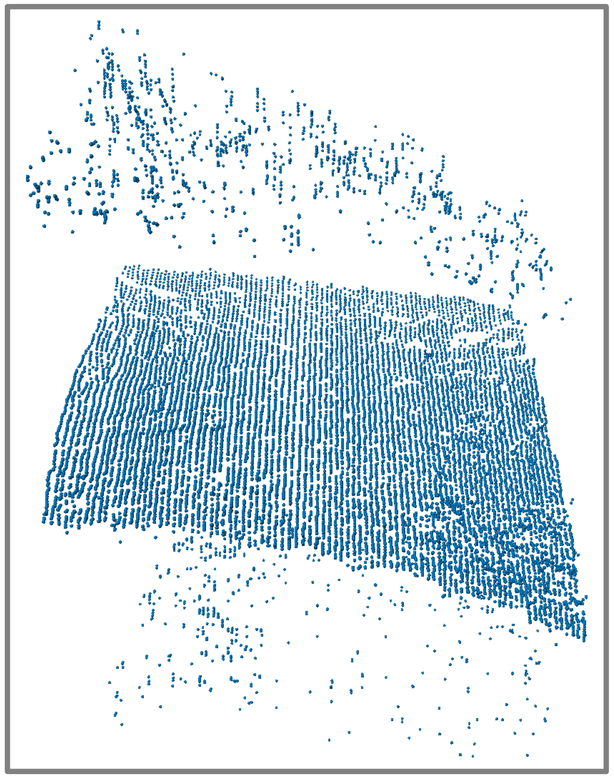

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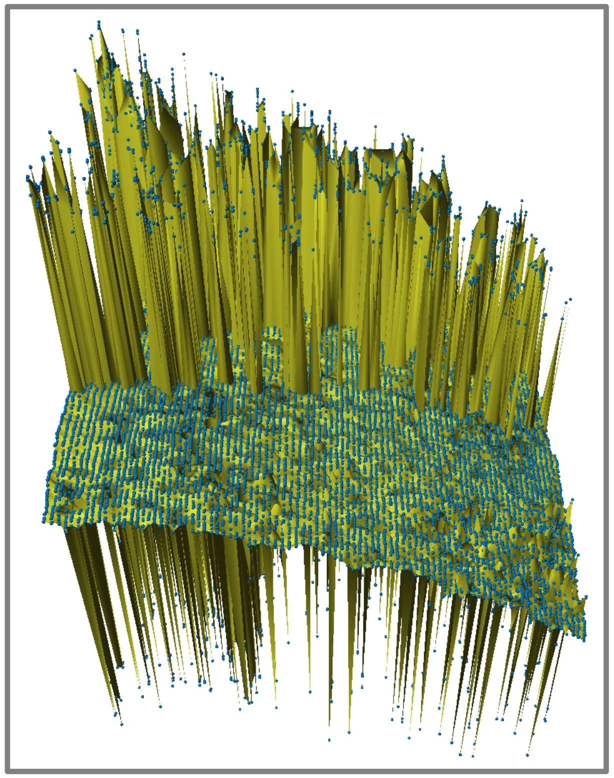

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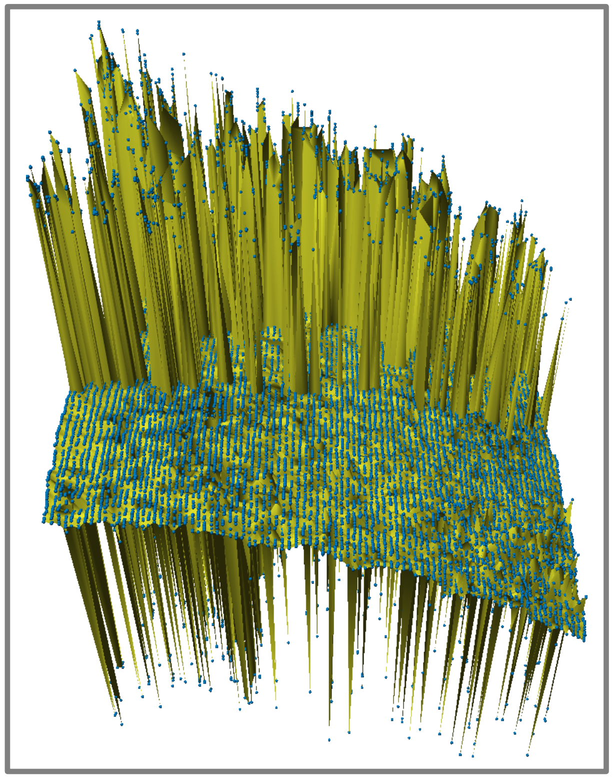
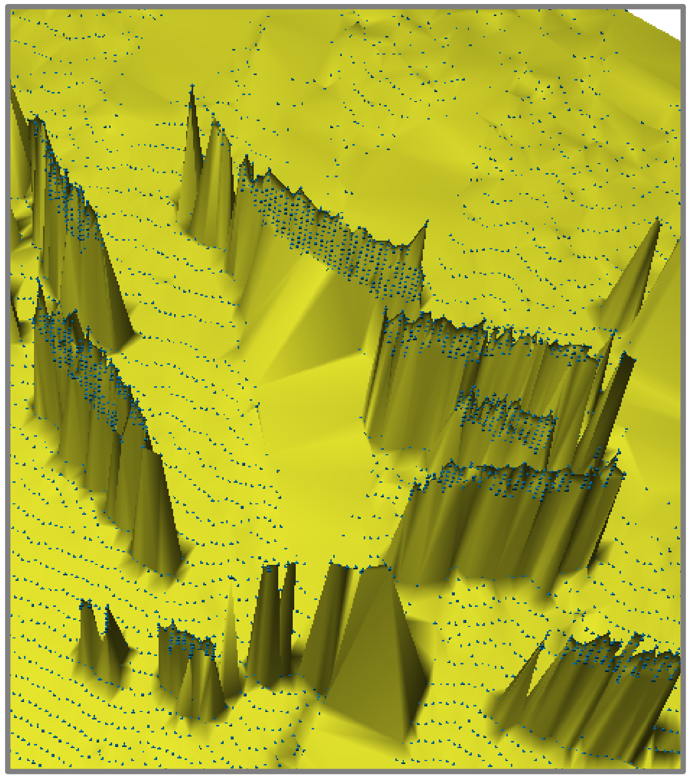
2. Non-permanent physical objects (e.g. fish)





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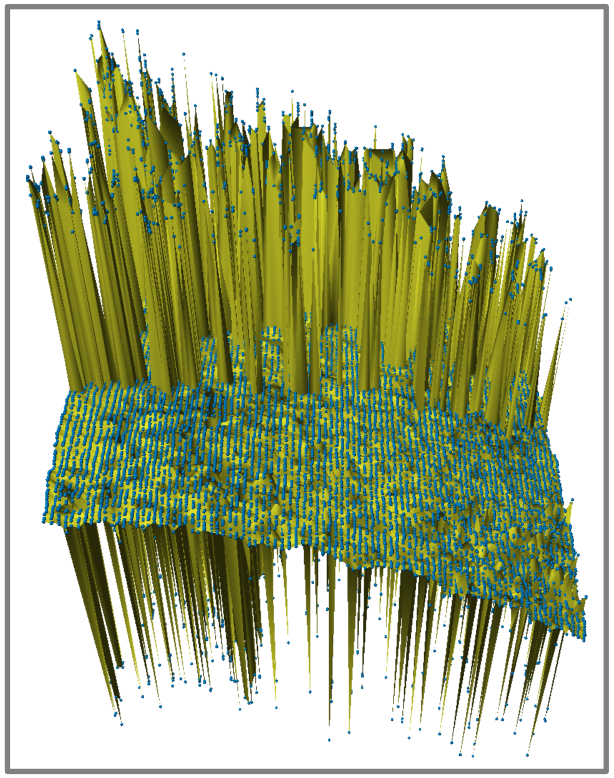

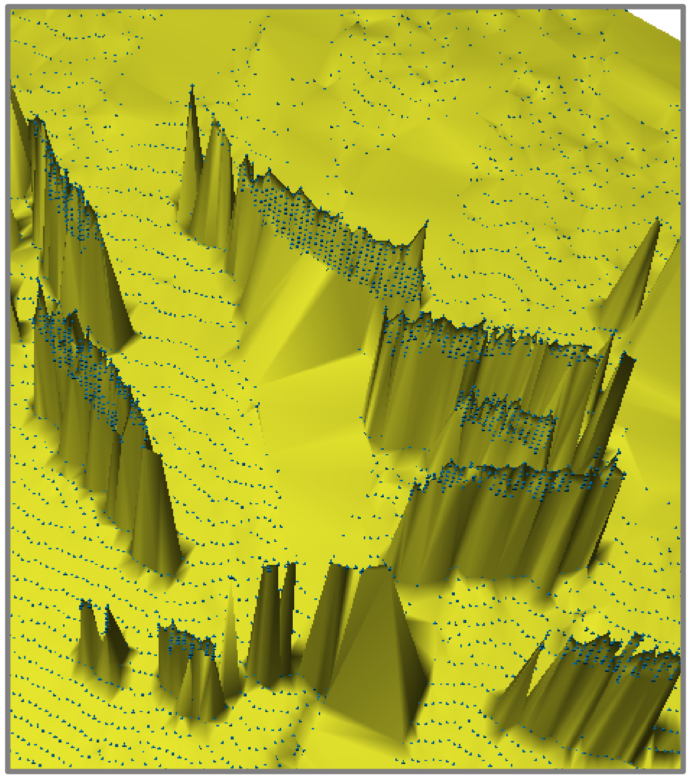

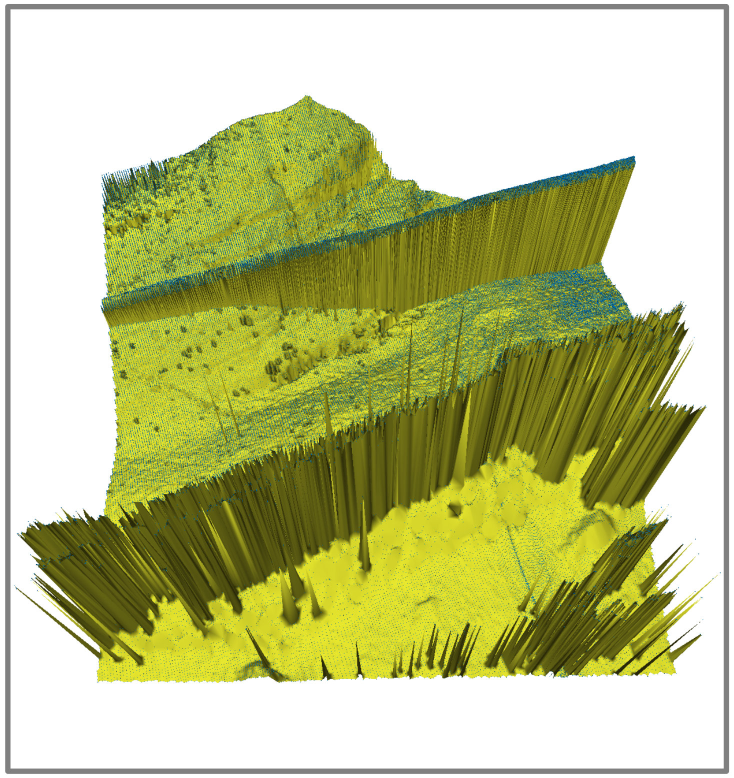

Noise types

Data: StatoilHydro

1. Random spikes, possibly clustered
2. Non-permanent physical objects (e.g. fish)
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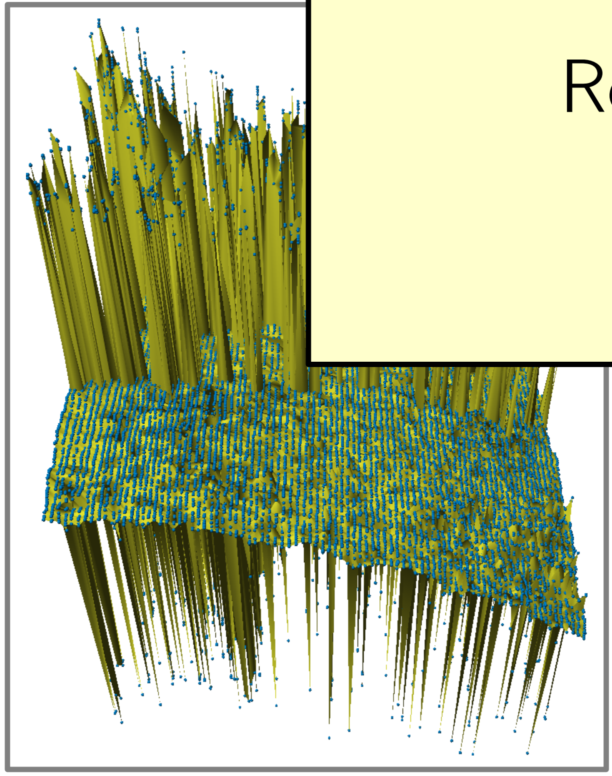
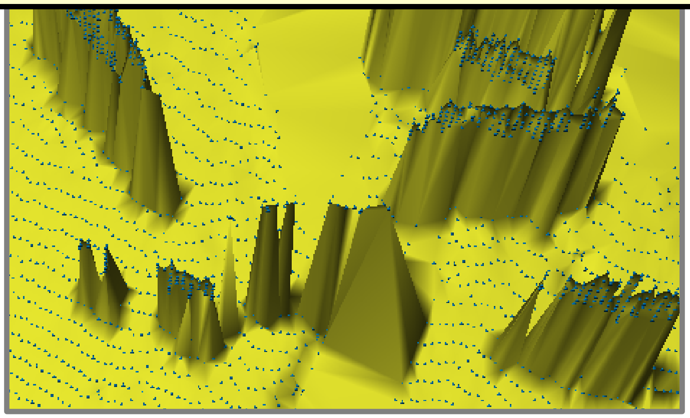
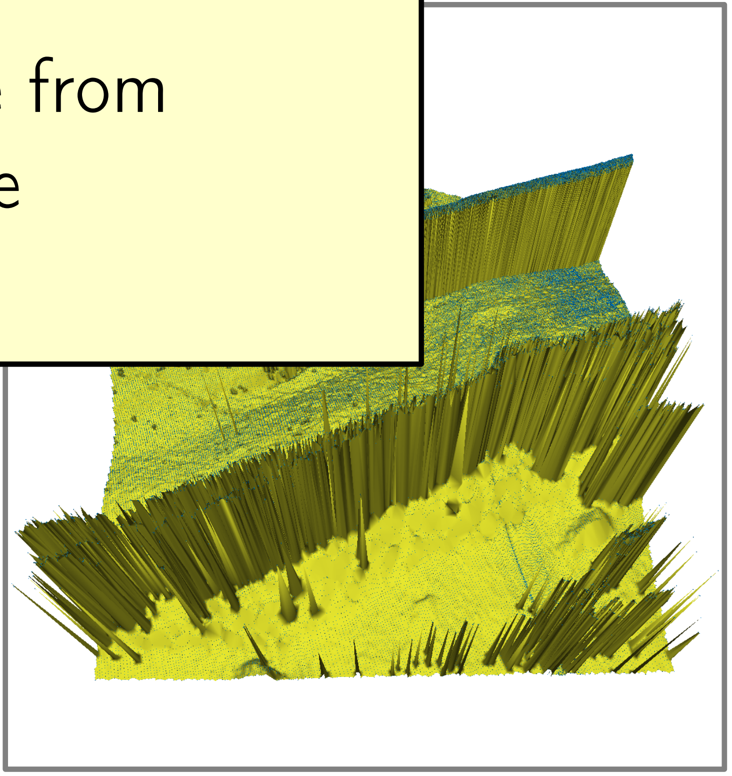
Problem

Remove these types of noise from massive point sets while keeping features intact

Previous work

Local-neighbourhood based

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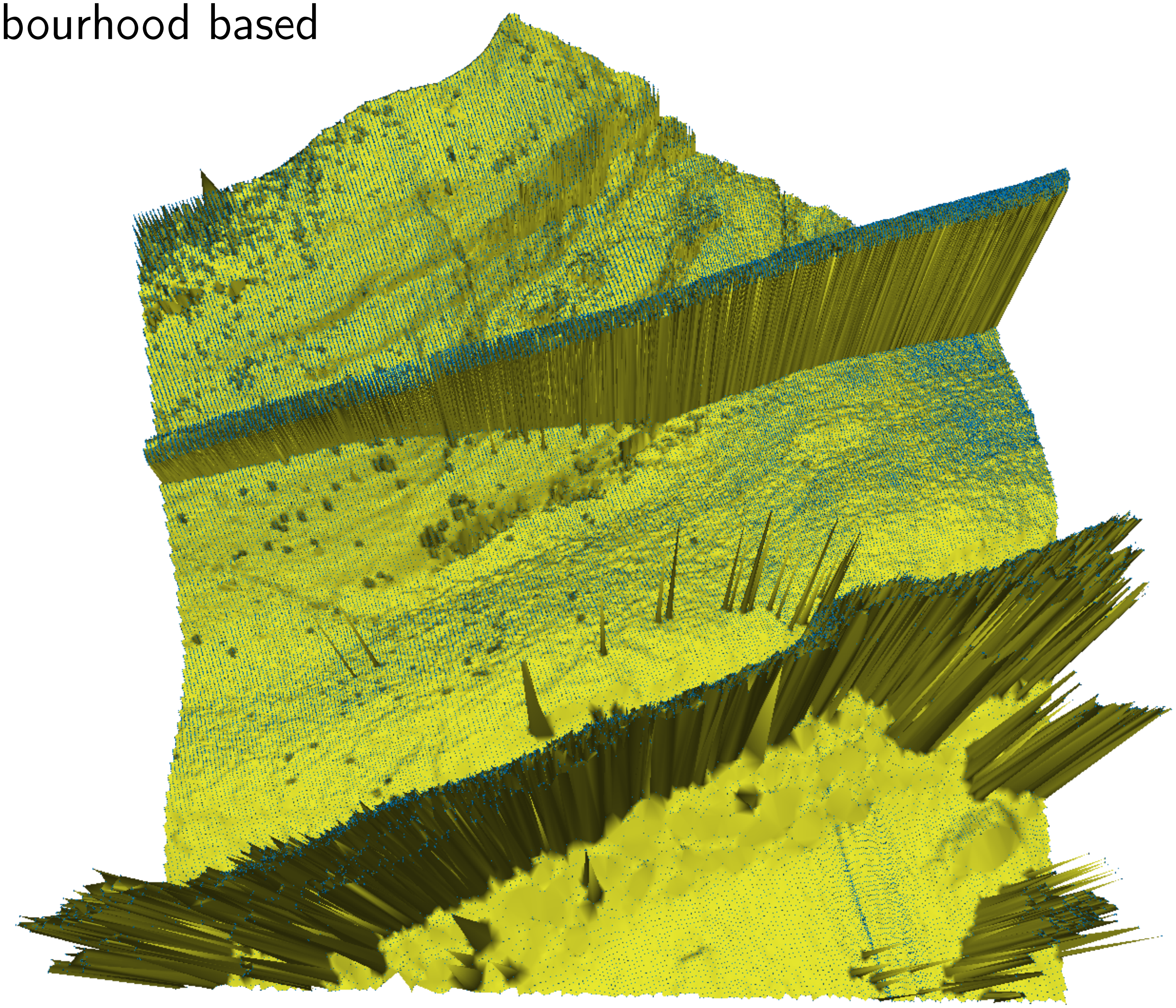

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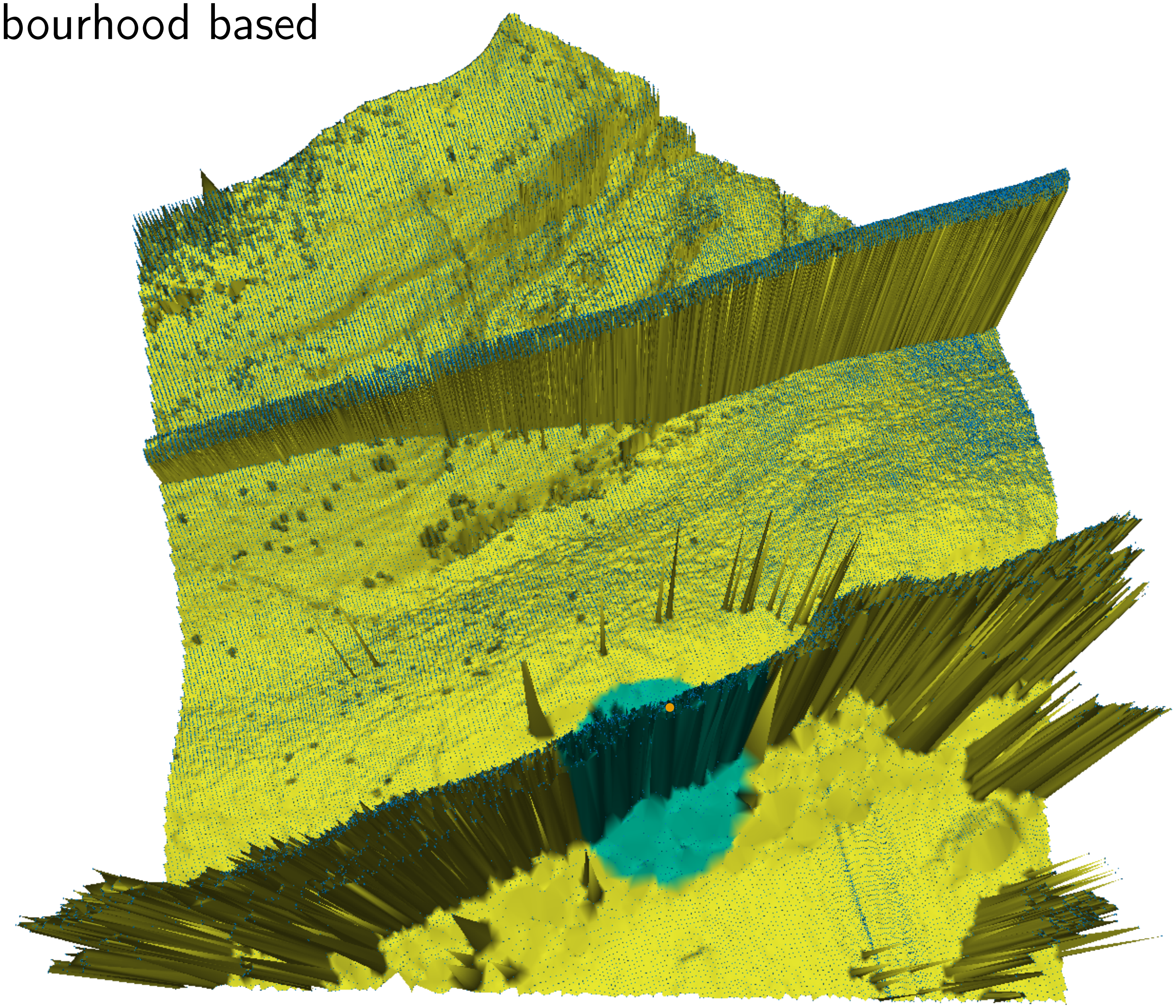

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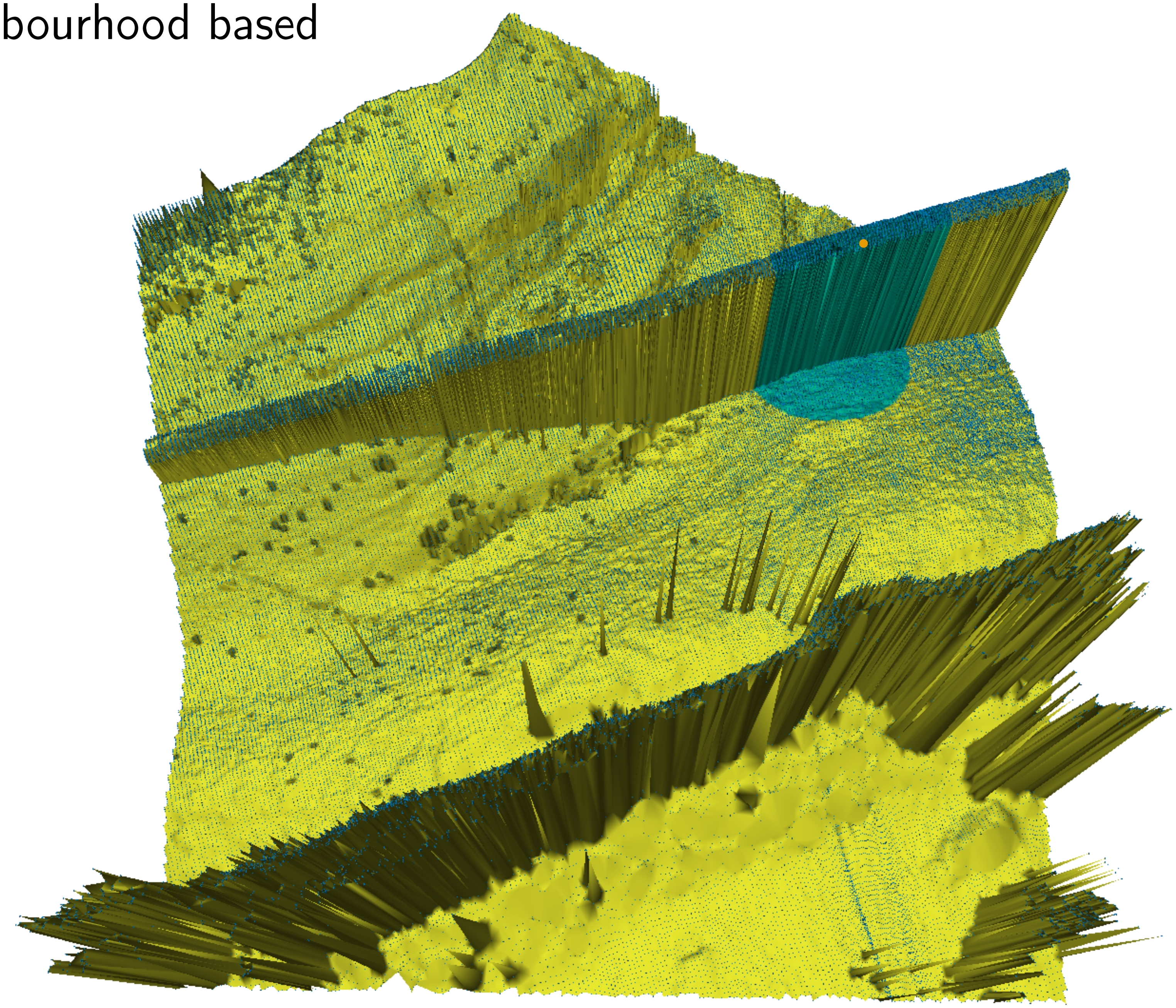

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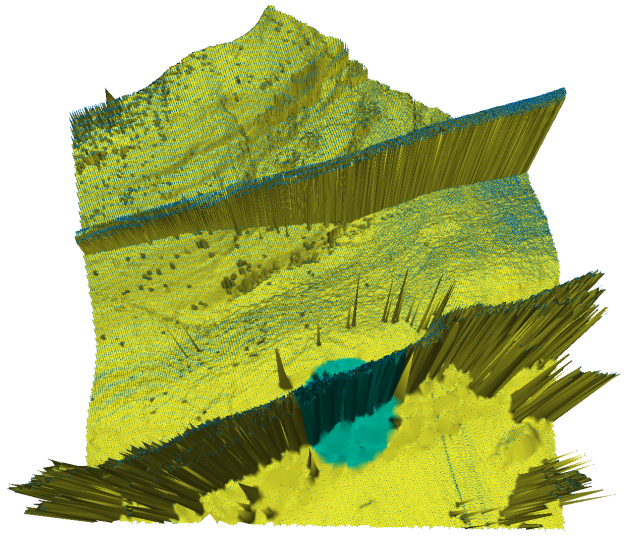
E.g. CUBE [Calder & Mayer 2003], industry standard

- Place grid over points
- Estimate heights at grid nodes
  - Stastical analysis of points in neighbourhood
- Remove points far away from estimated surface



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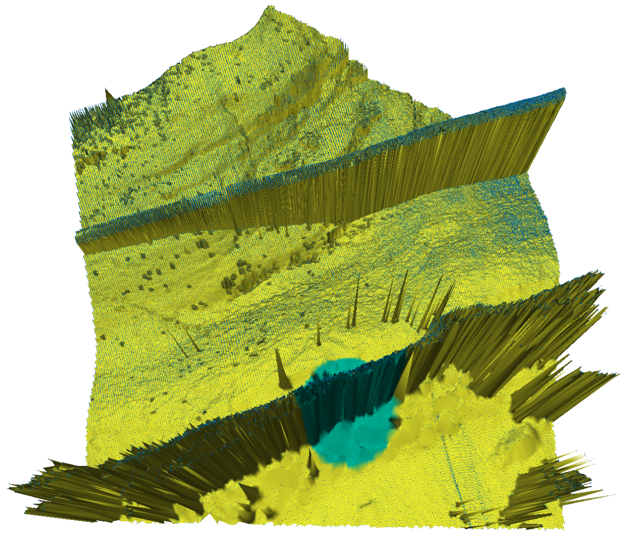

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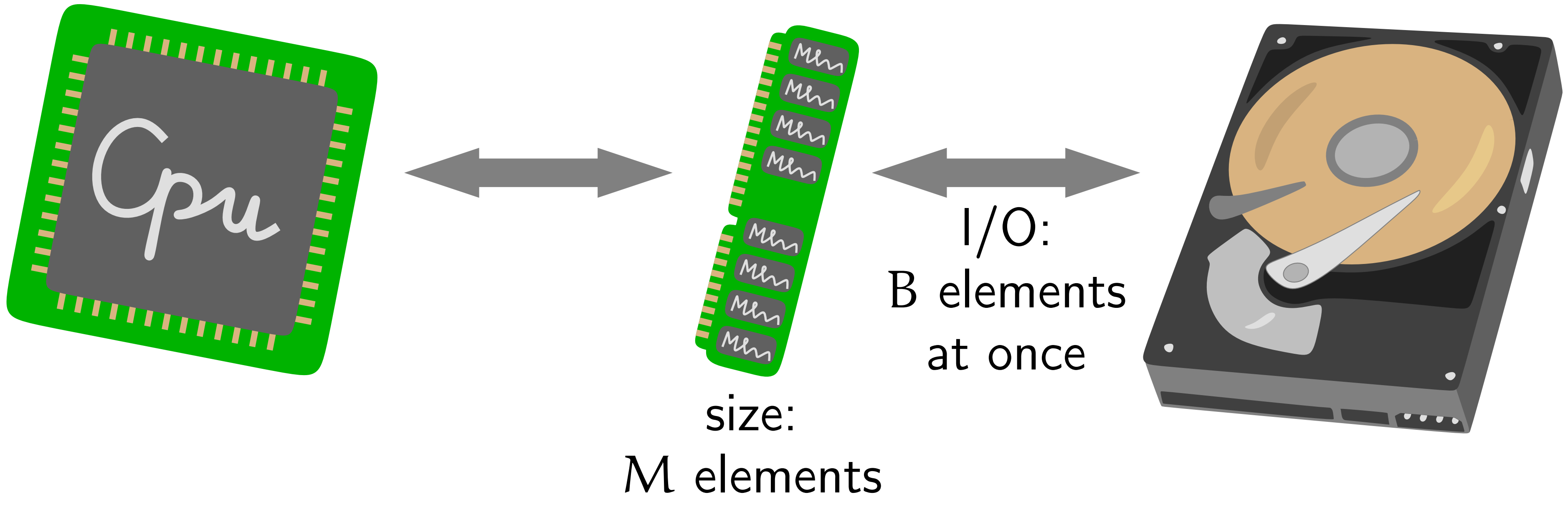
$\longrightarrow$ Problems handling large clusters of noise and structural noise (types 2 and 3)

I/O-efficient algorithms

I/O model: analyze number of data transfers between internal and external memory



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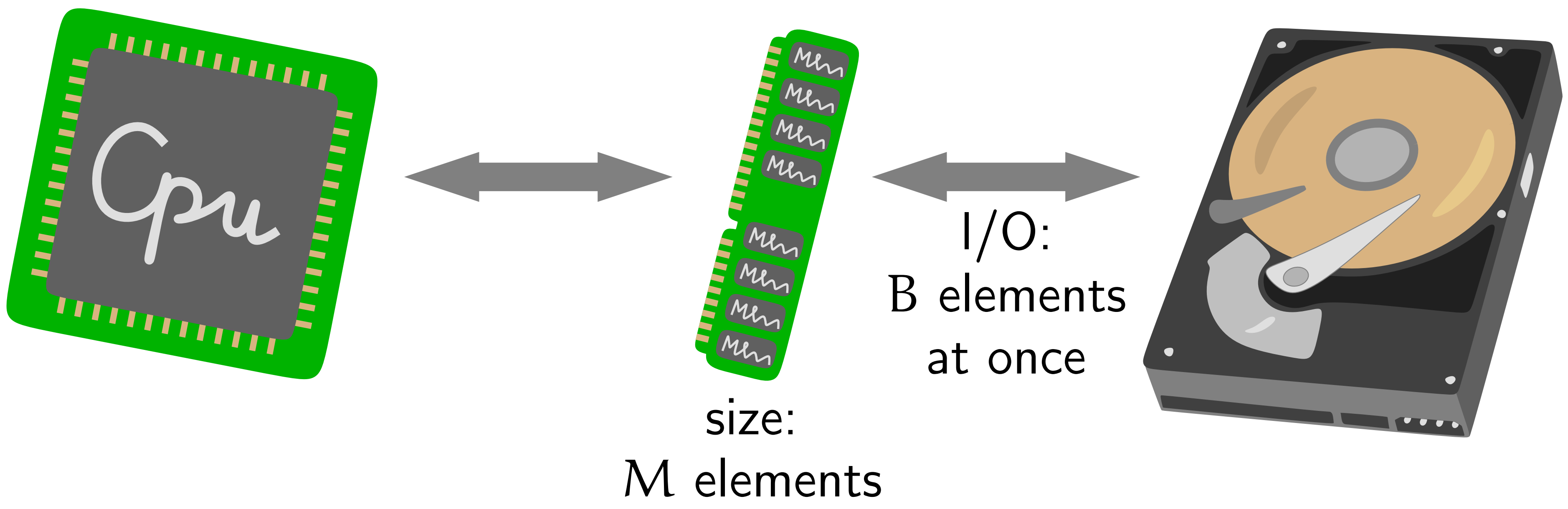

- Scanning N elements:
  $\Theta(\mathrm{scan}(N)) = \Theta(N/B)$ I/Os

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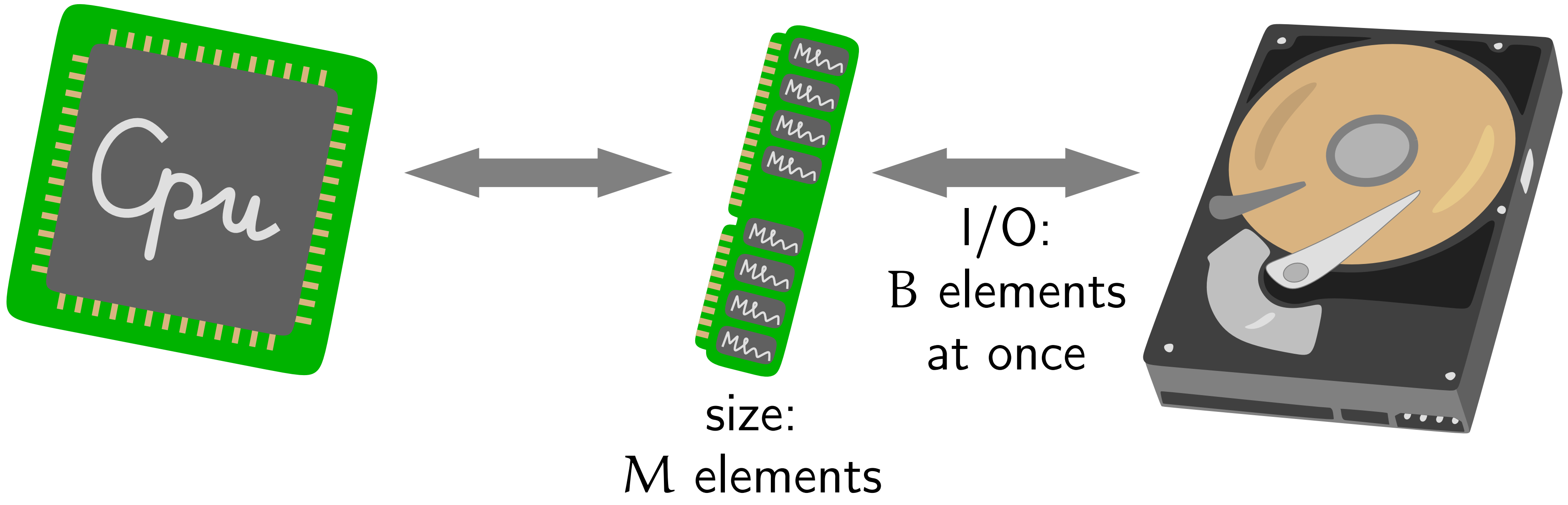

- Scanning N elements:
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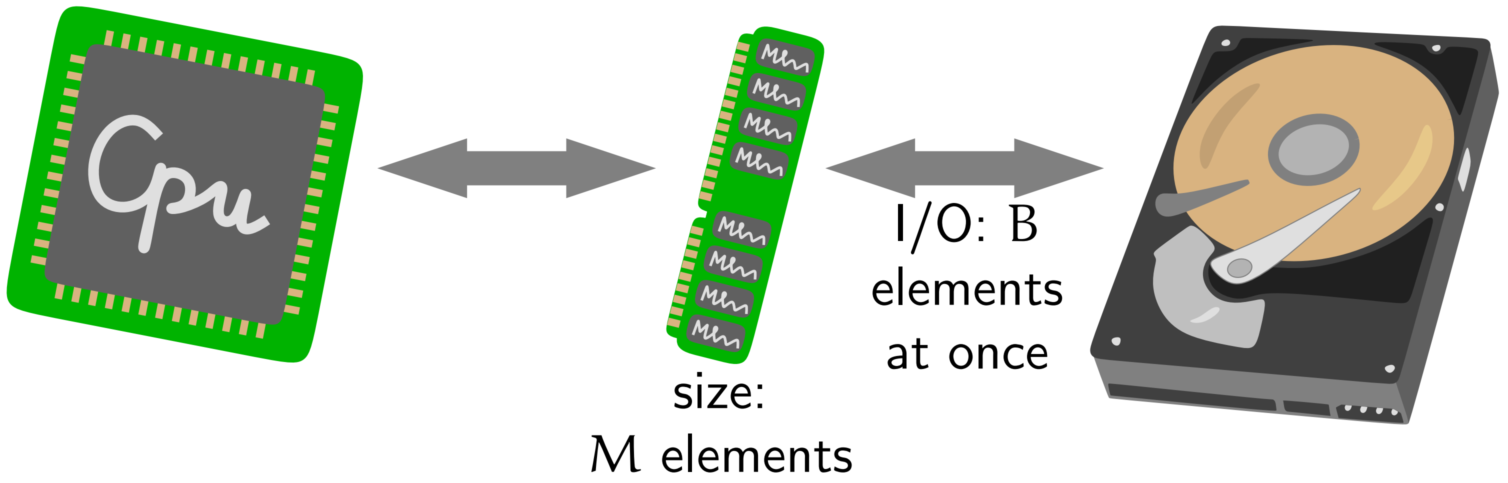
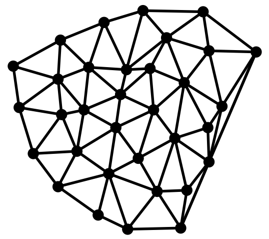
- Sorting N elements:
  $\Theta(\mathtt{sort}(N)) = \Theta(N/B \ \mathtt{log}_{M/B} N/B)$ I/Os

I/O-efficient algorithms

Previous work



Delaunay triangulation for computing a TIN DEM



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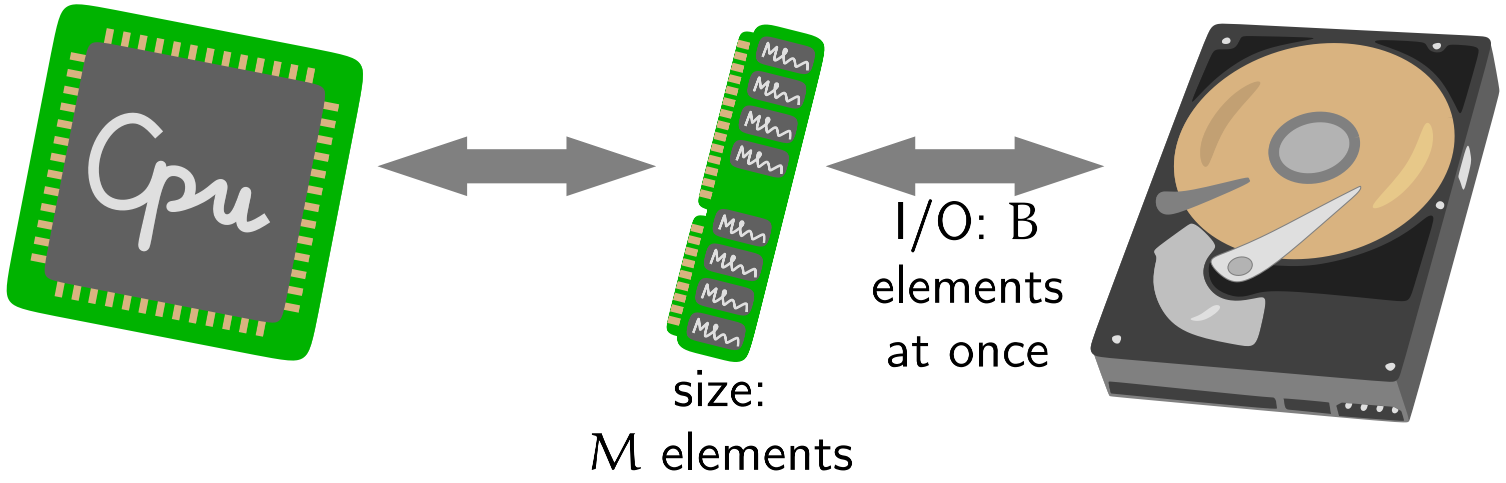

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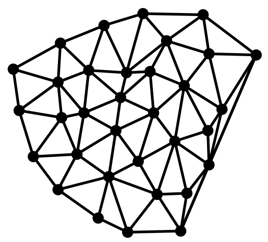

- $O(\mathtt{sort}(N))$ [Goodrich et al. 1993, Kumar & Ramos 2002]
- Practical $O(\mathtt{sort}(N))$ [Agarwal et al. 2005]

I/O-efficient algorithms

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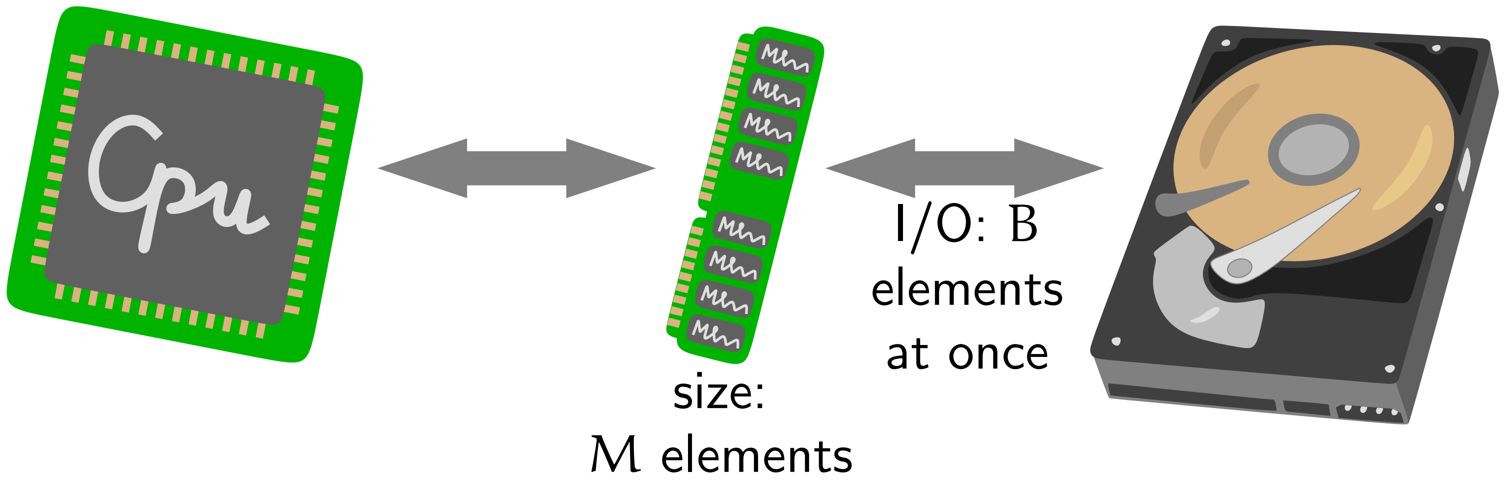
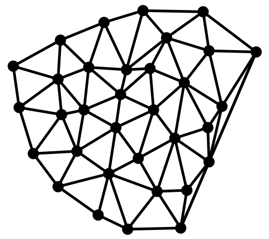


Delaunay triangulation for computing a TIN DEM



- $O(\mathtt{sort}(N))$ [Goodrich et al. 1993, Kumar & Ramos 2002]
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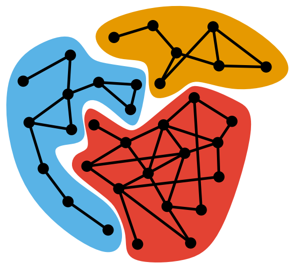
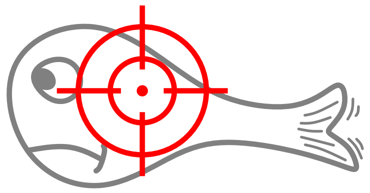
Connected components



- $O(\mathtt{sort}(|E|)\,\mathtt{log}_2\mathtt{log}_2(B\frac{|V|}{|E|}))$ [Munagala and Ranade 1999]
- Practical $O(\mathtt{sort}(N)\,\mathtt{log}_2(N/M))$ [Agarwal et al. 2006] (batched union–find)

Our results

- Cleaning algorithm for MBES data
  - Identifies both random, local and structural noise
  - Theoretically I/O-efficient
  - Practically efficient and implementable



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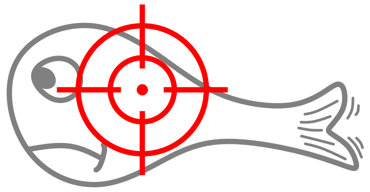
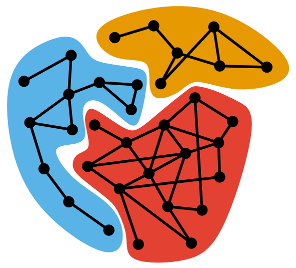


- Connected component algorithm
  - $O(\mathtt{sort}(N))$ I/Os under a natural assumption
  - Practically efficient and implementable



Our cleaning algorithm

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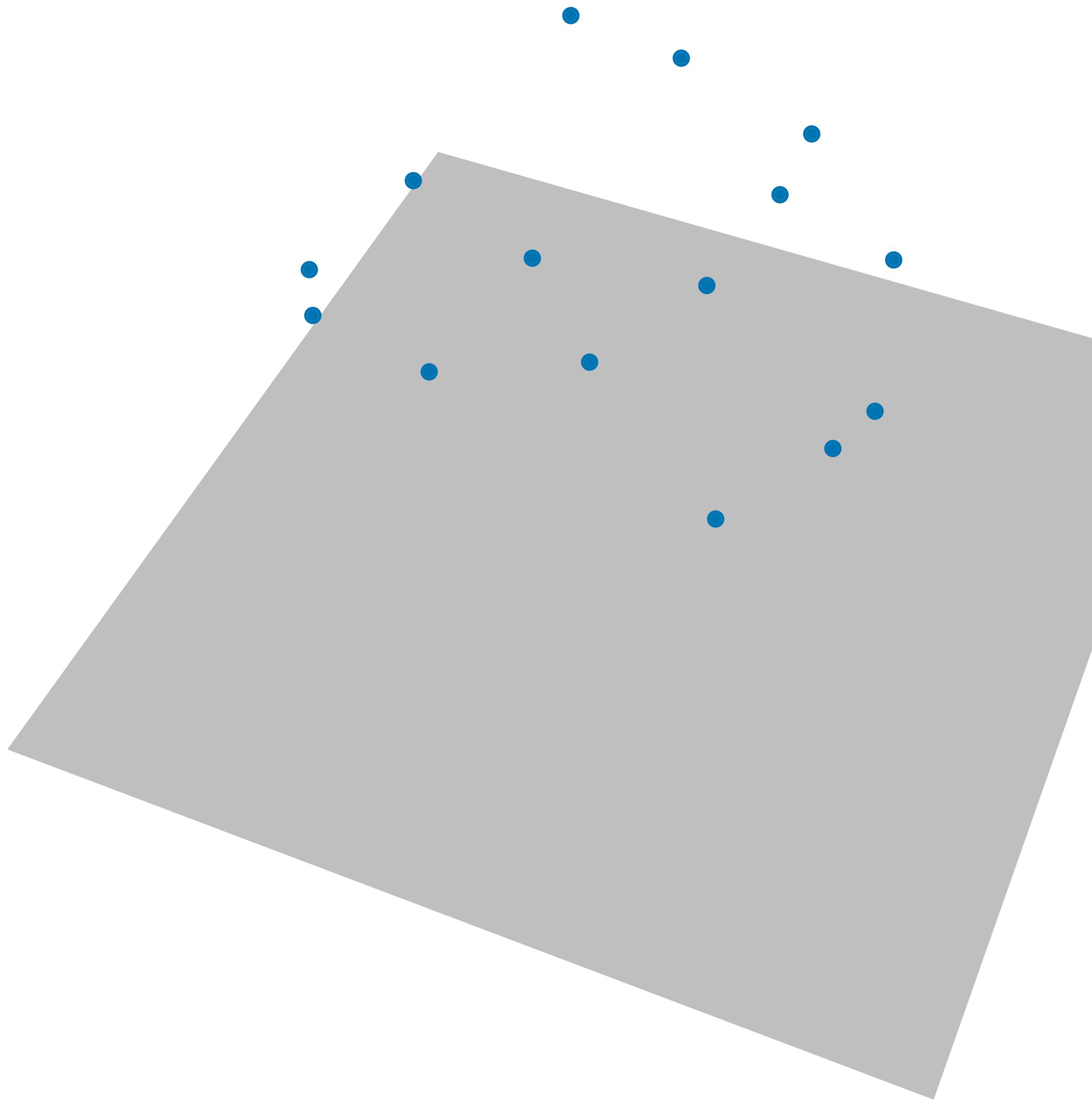

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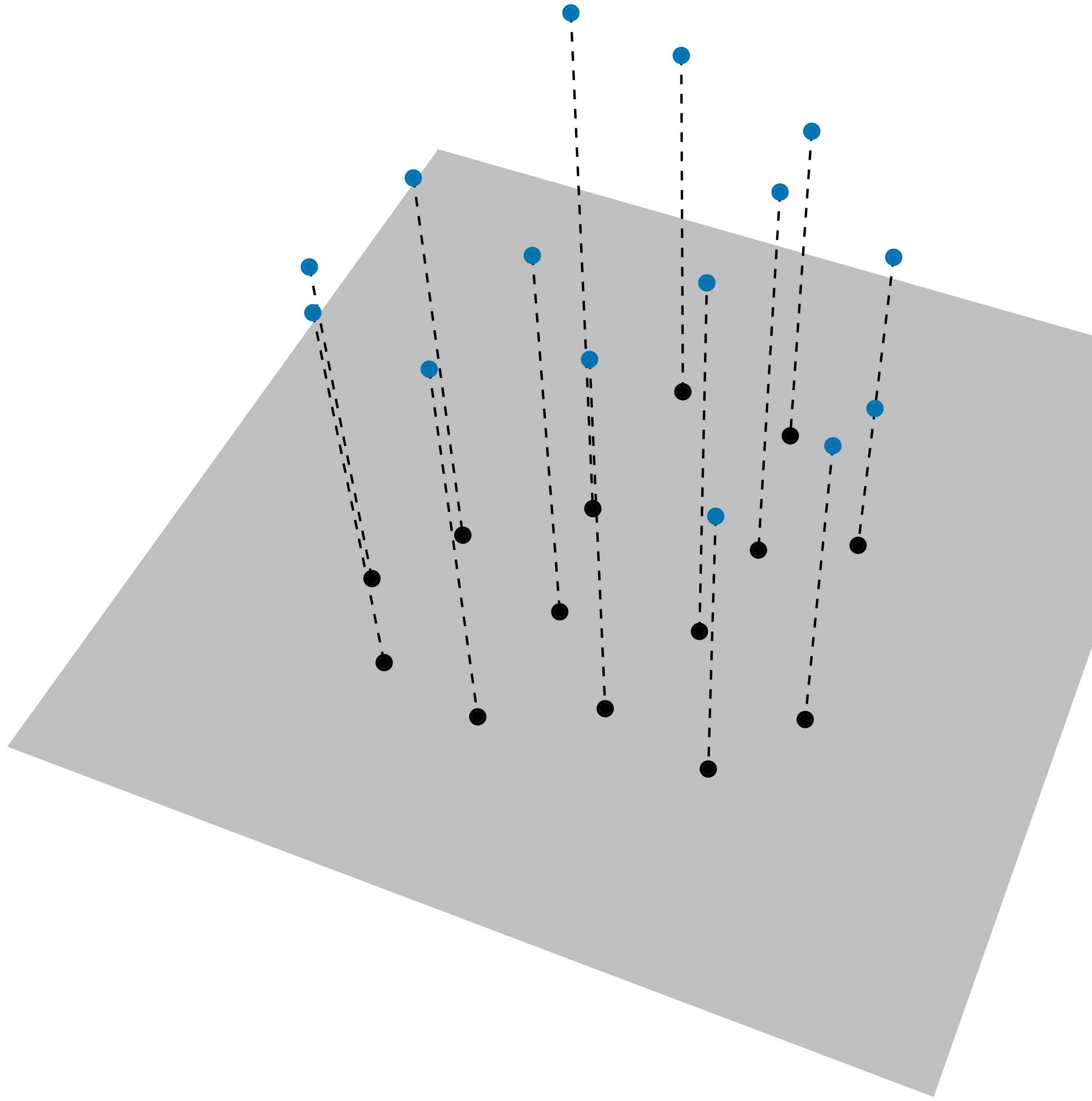

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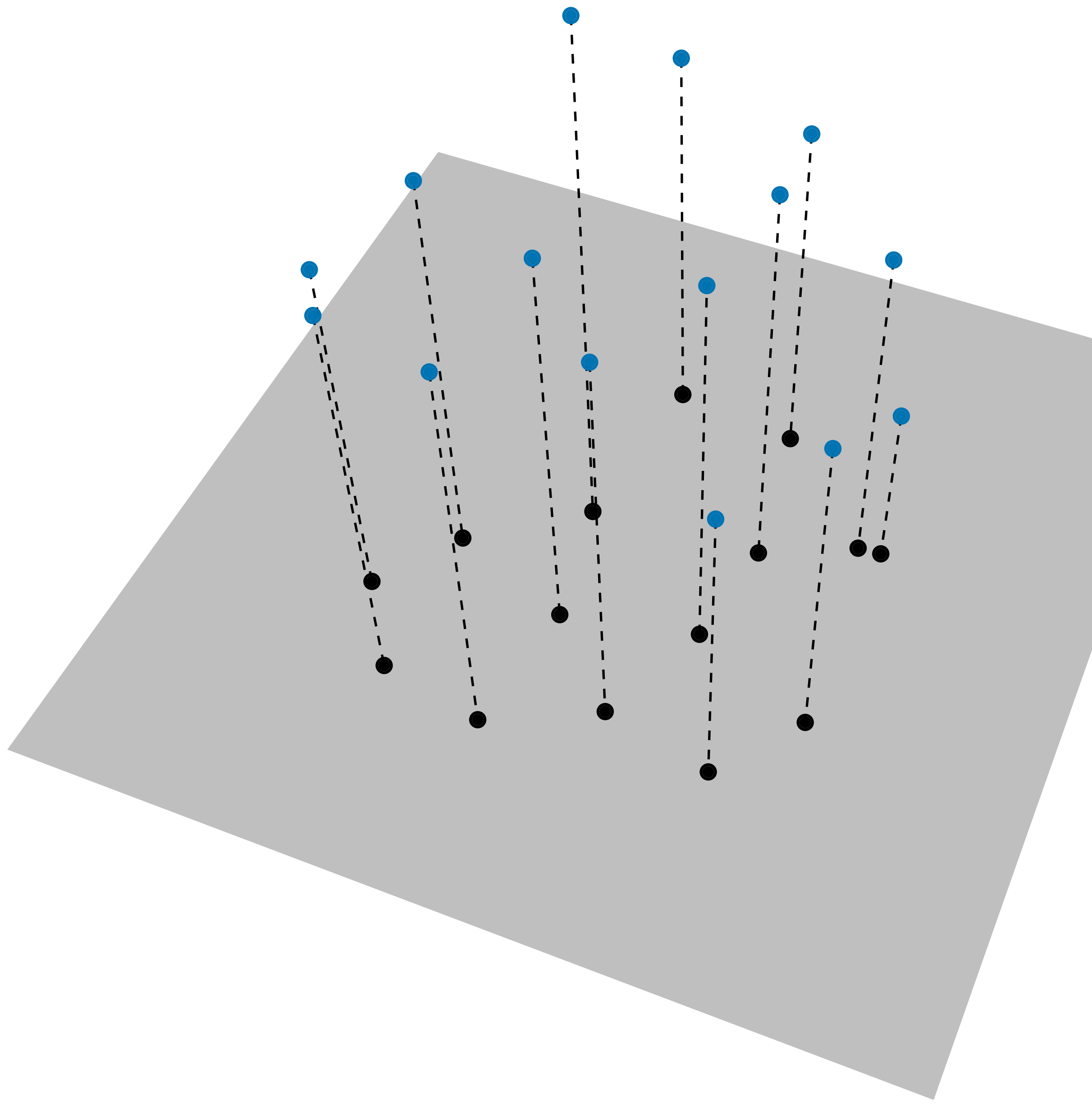
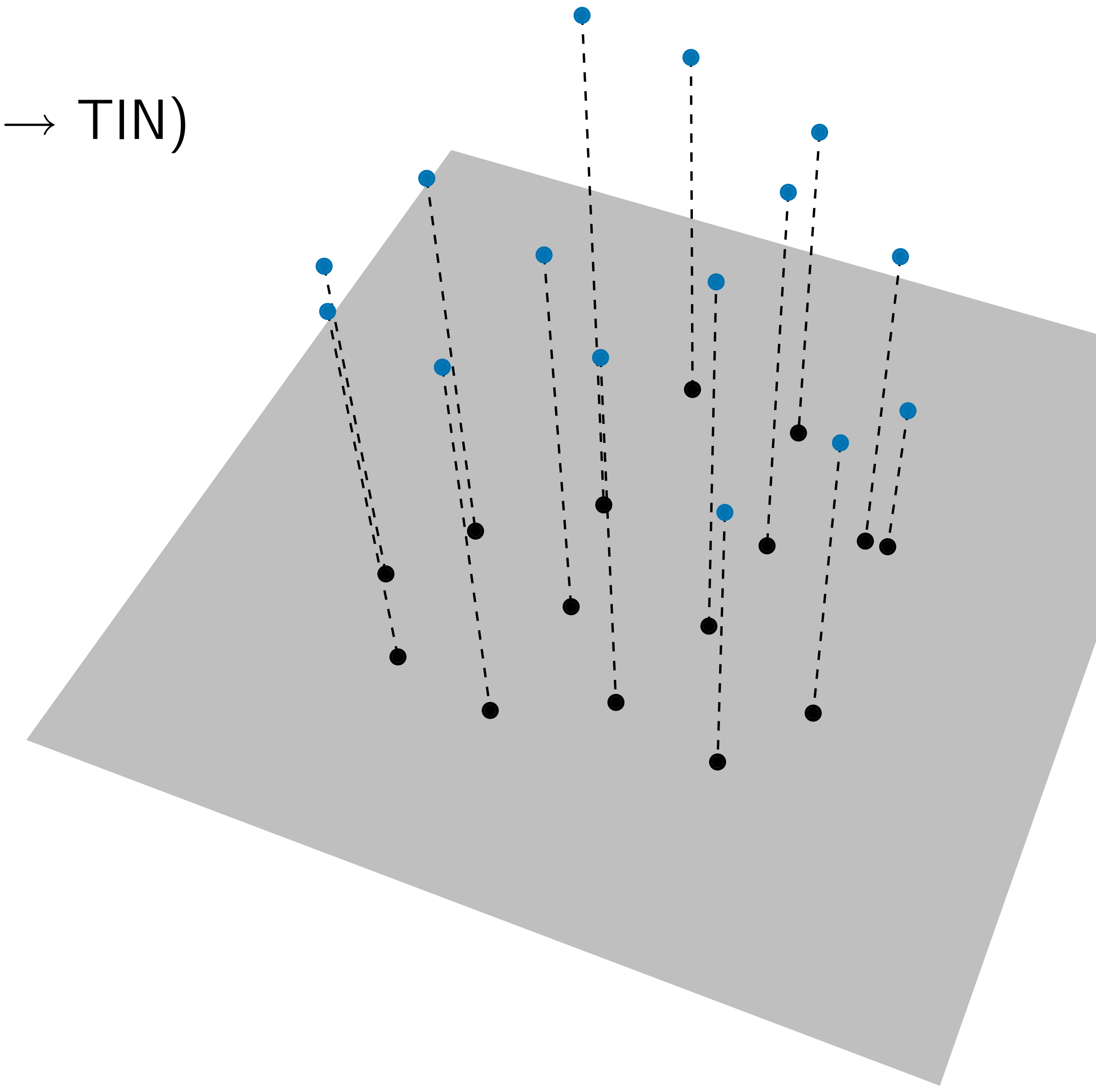


Our cleaning algorithm

1. Perturb "xy-duplicate" points
2. Create Delaunay triangulation ($\rightarrow$ TIN)



Our cleaning algorithm

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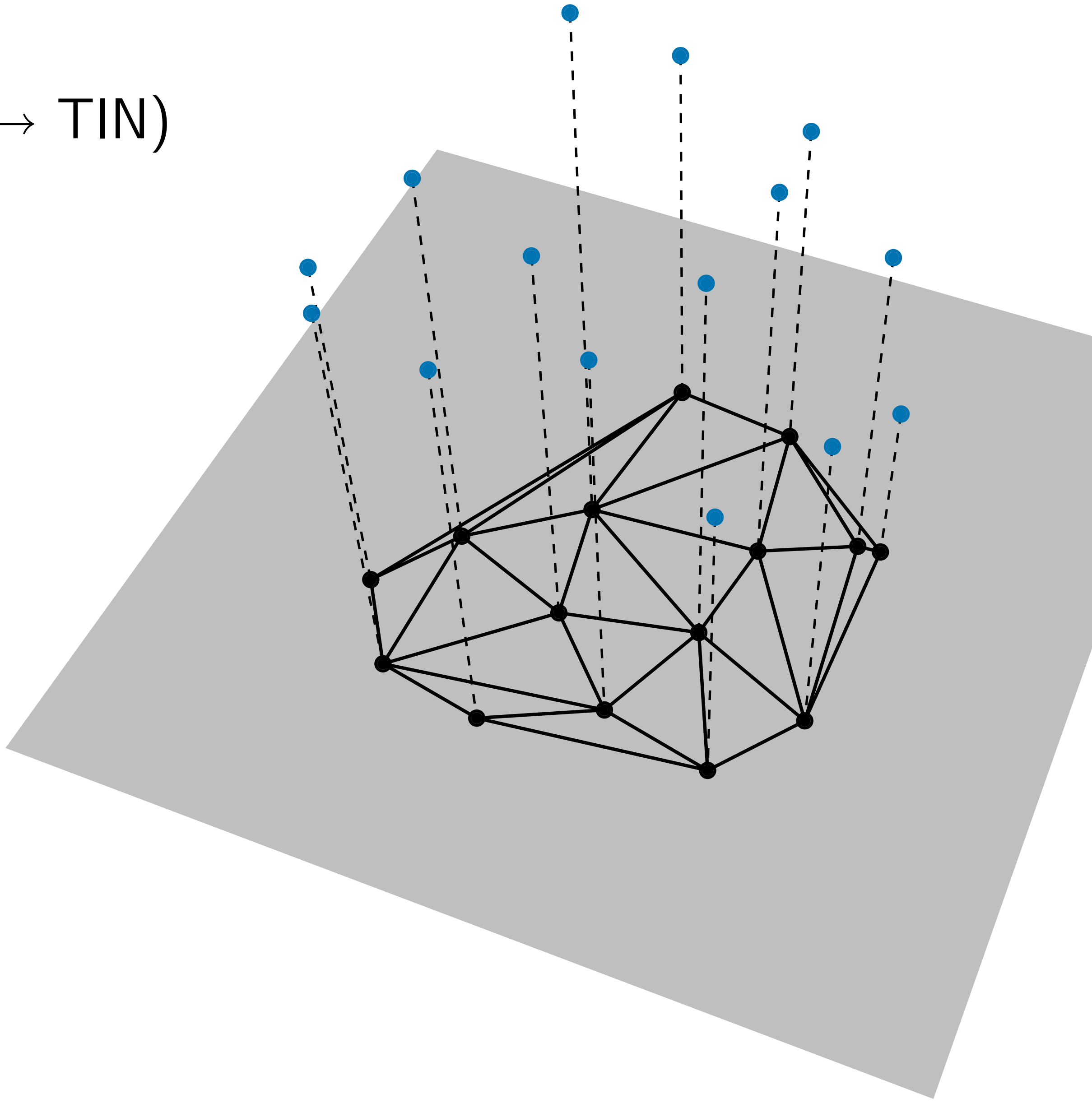

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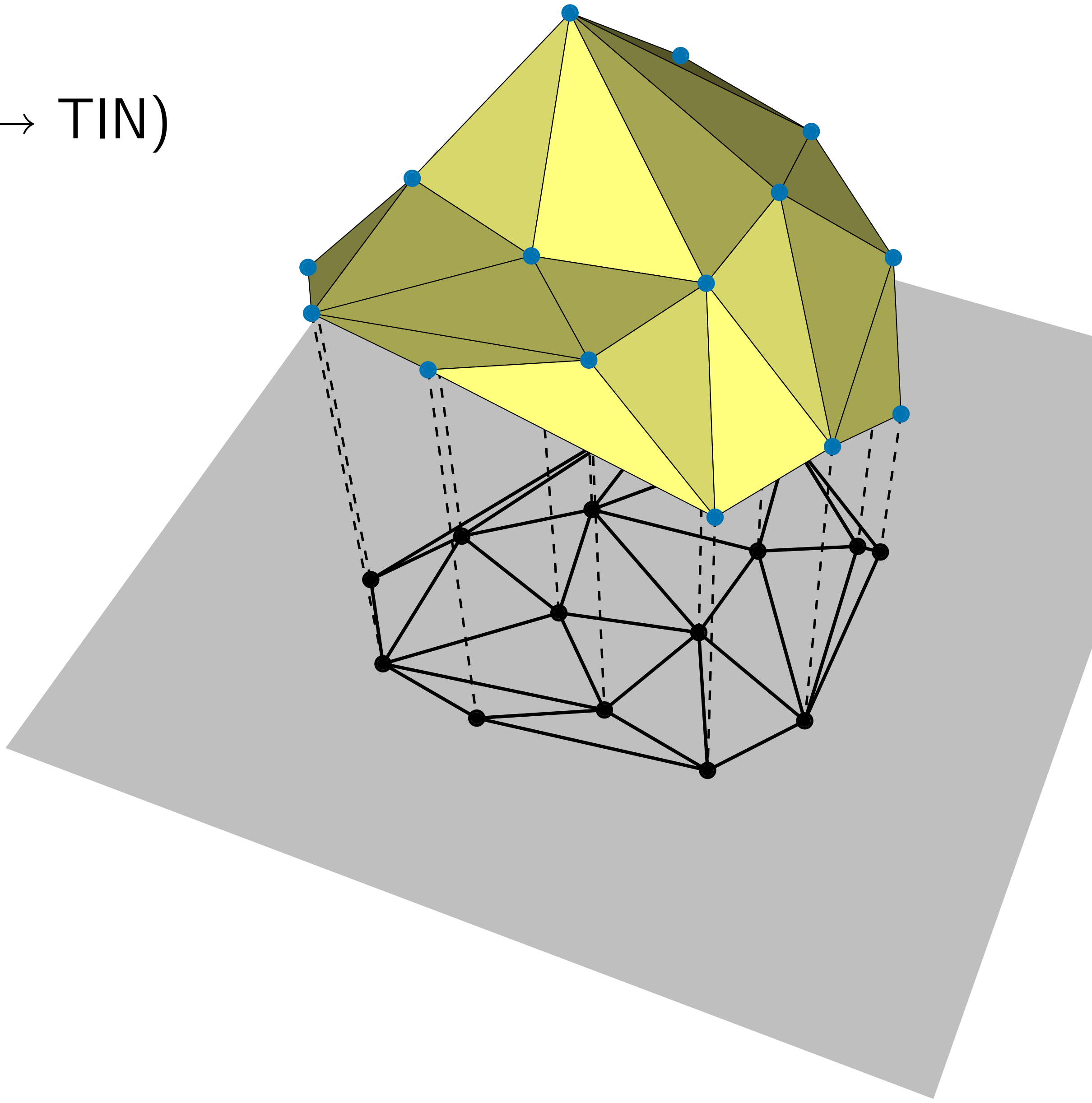

Our cleaning algorithm

1. Perturb "xy-duplicate" points
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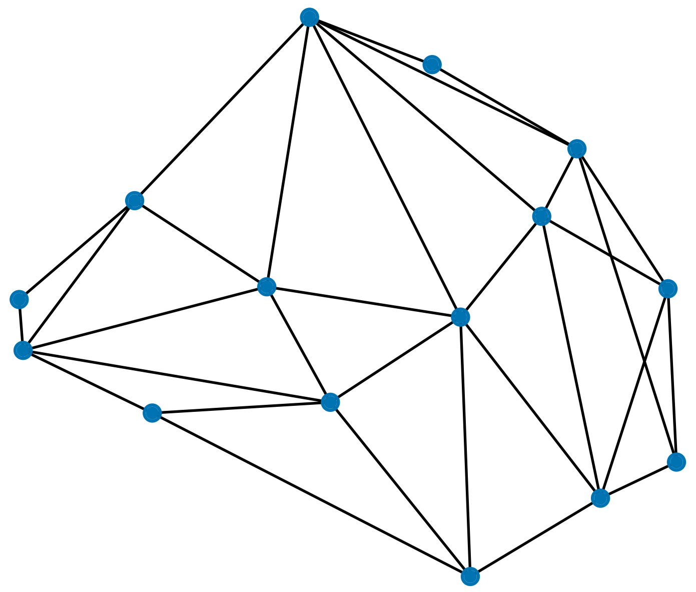
3. Add *diagonals*



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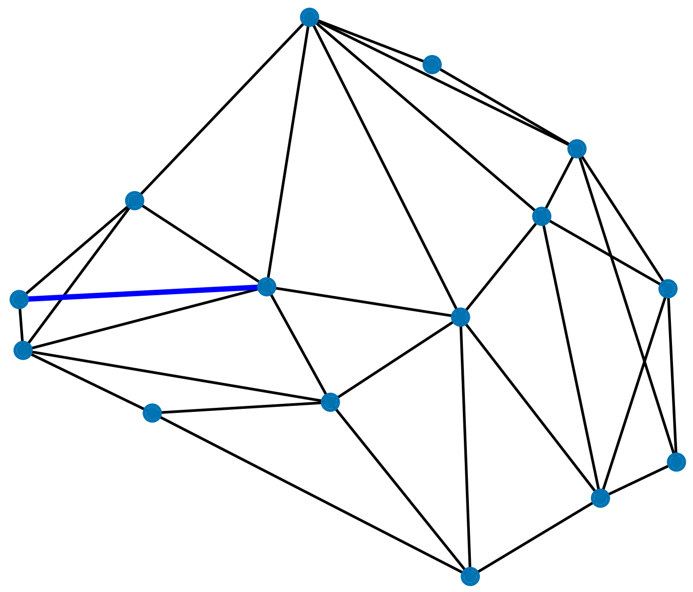

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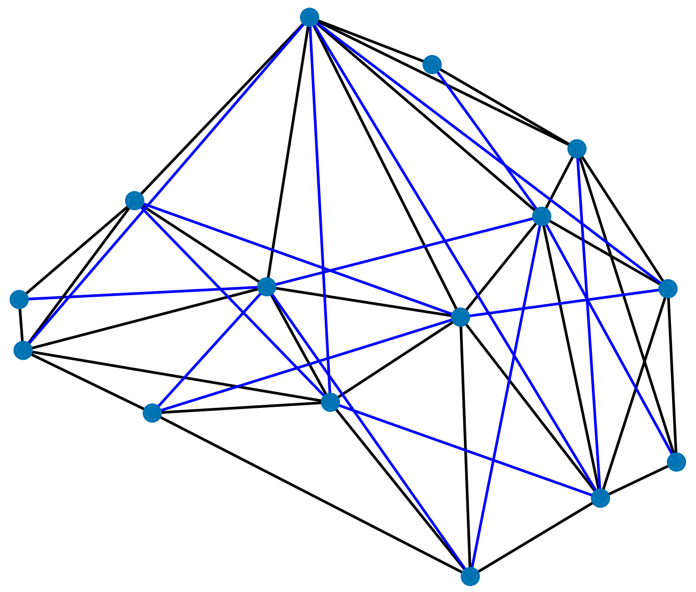

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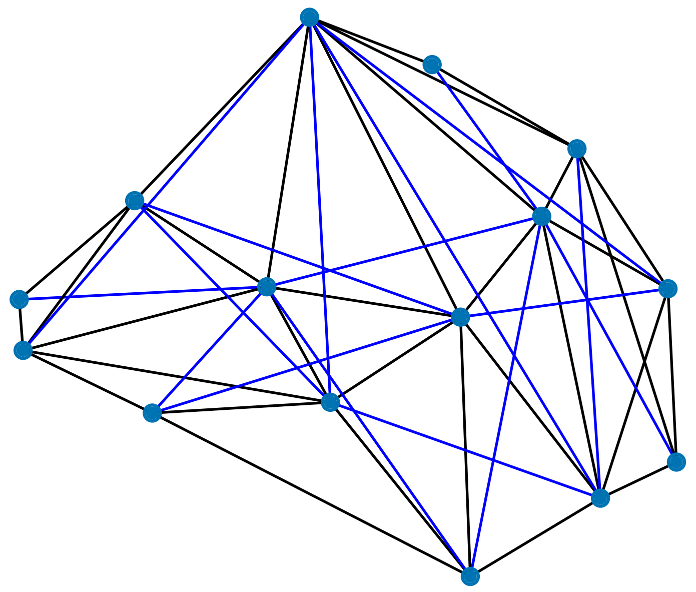
4. Remove edges with z-difference $>$ threshold



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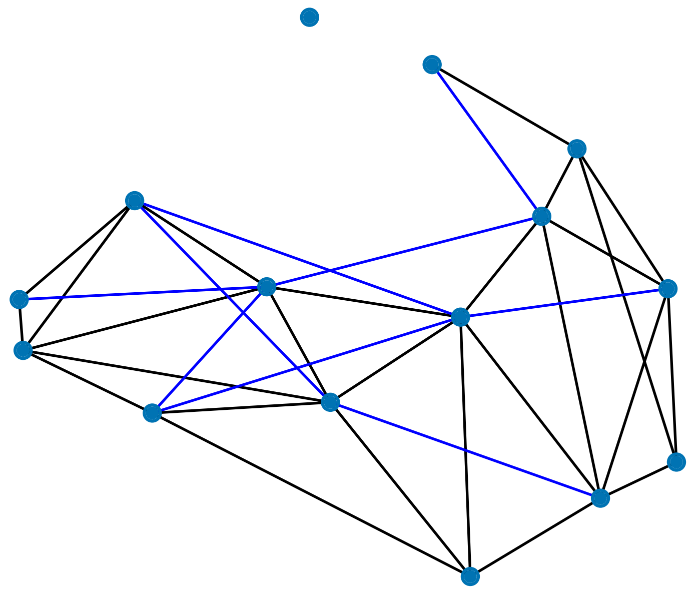
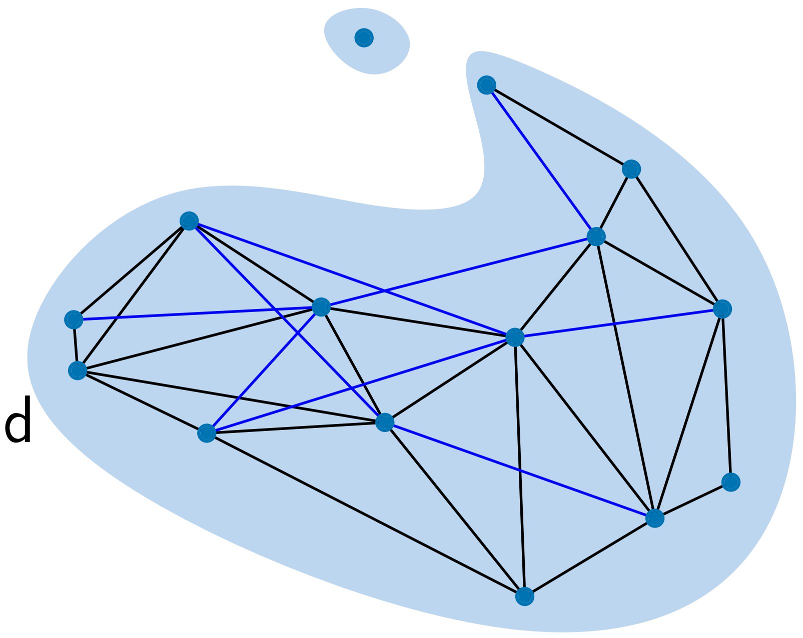


Our cleaning algorithm

1. Perturb "xy-duplicate" points
2. Create Delaunay triangulation ($\rightarrow$ TIN)
3. Add *diagonals*
4. Remove edges with z-difference $>$ threshold
5. Find largest connected component



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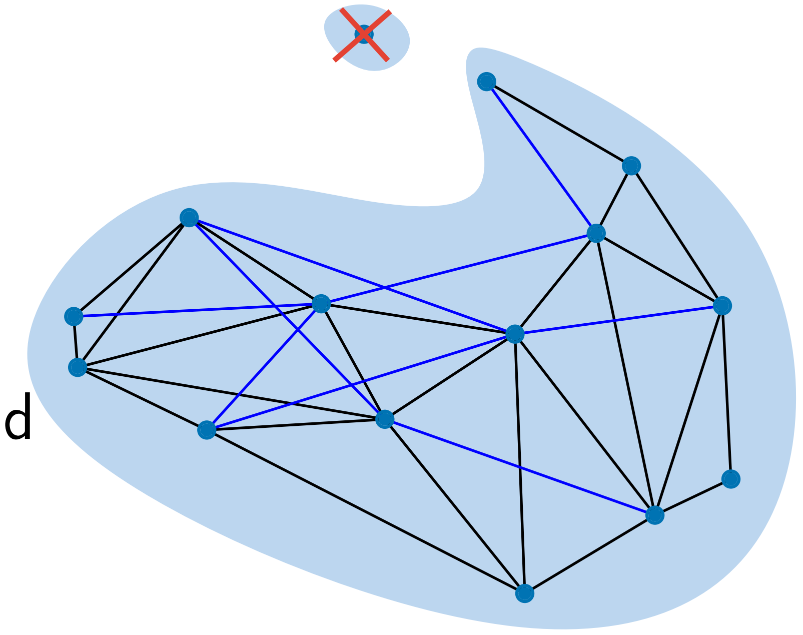
5. Find largest connected component
6. Remove all points not in largest component



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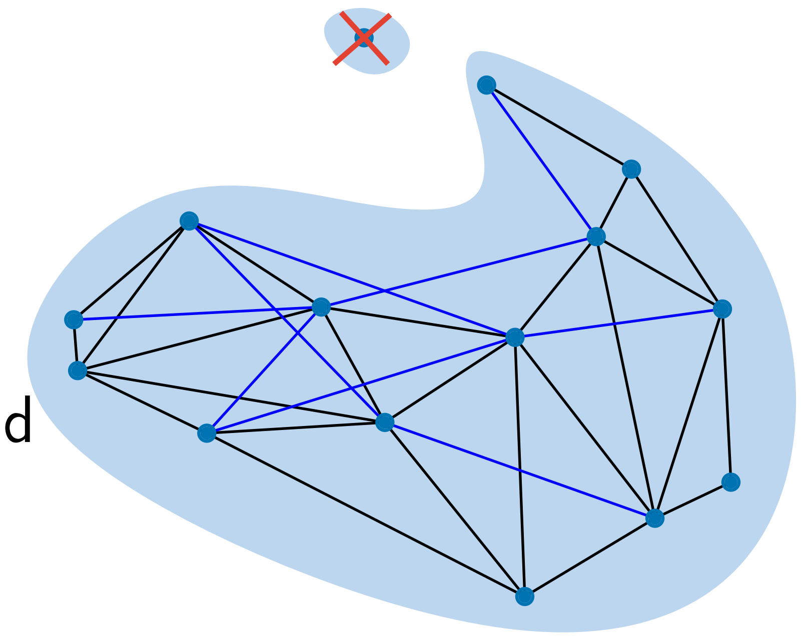
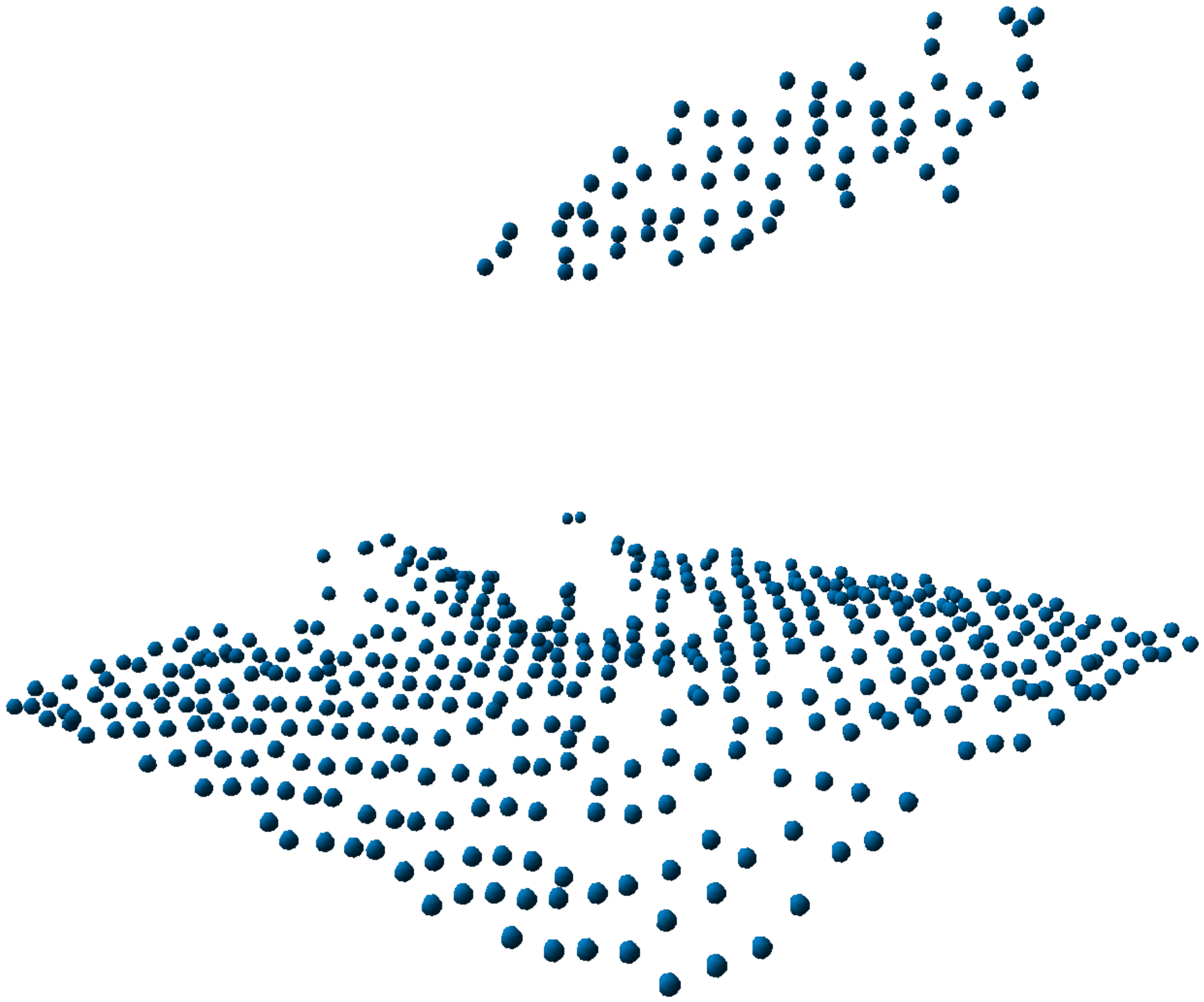


$O(\texttt{sort}(N))$ I/Os + connected components = $O(\texttt{sort}(N) \log\log B)$ I/Os, or $O(\texttt{sort}(N))$ I/Os under a practical assumption

Why it works

fish

Data: StatoilHydro



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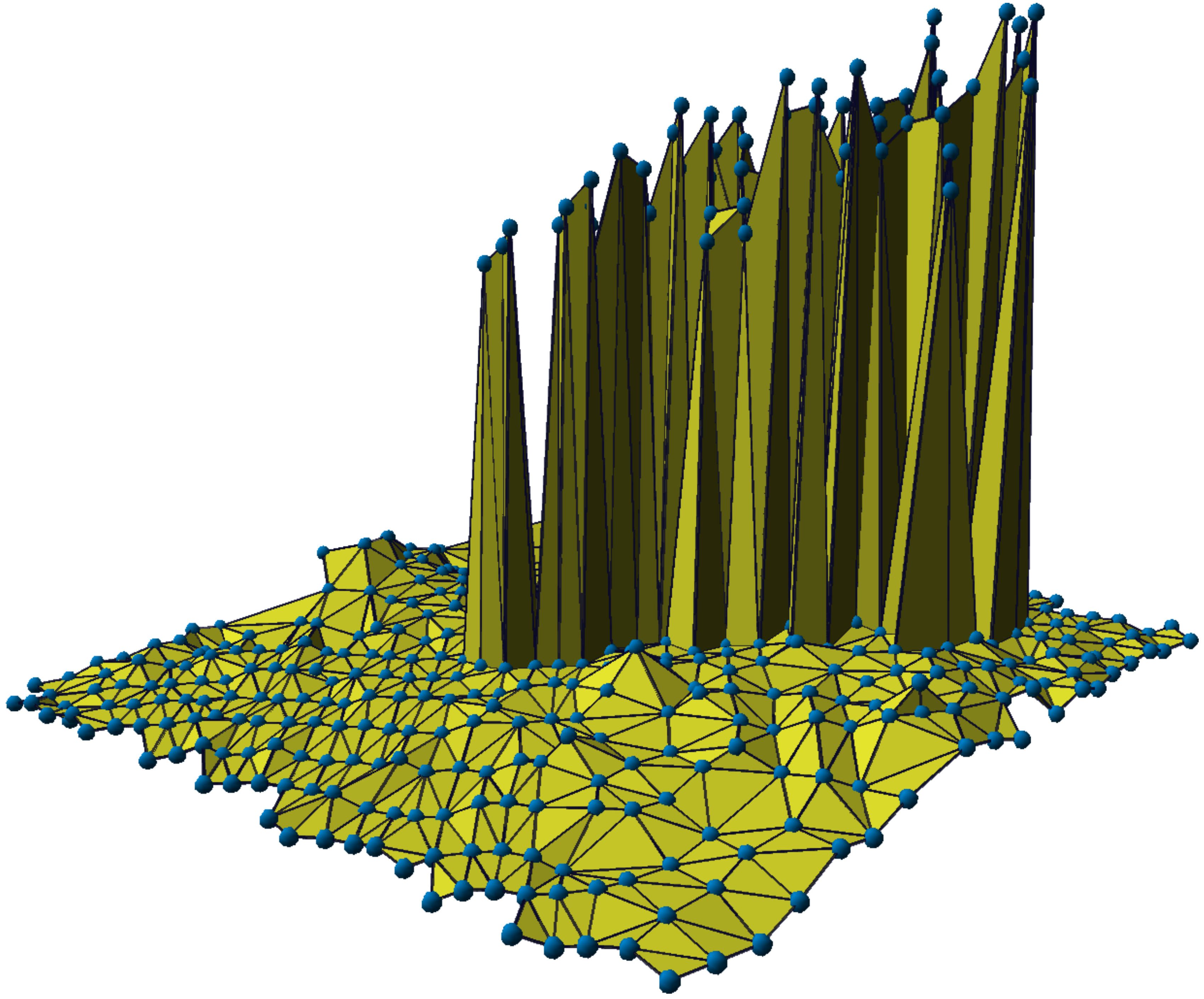

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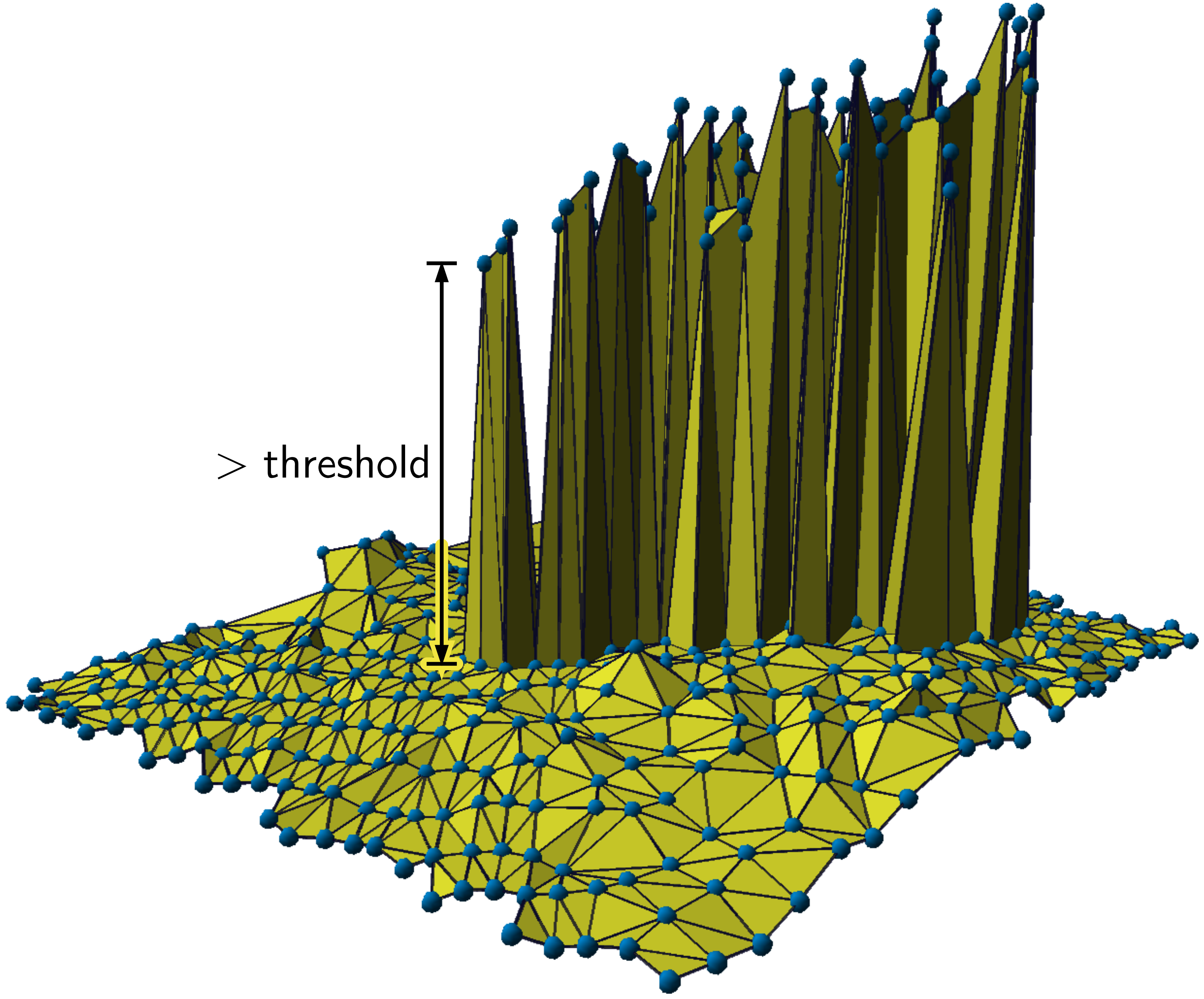

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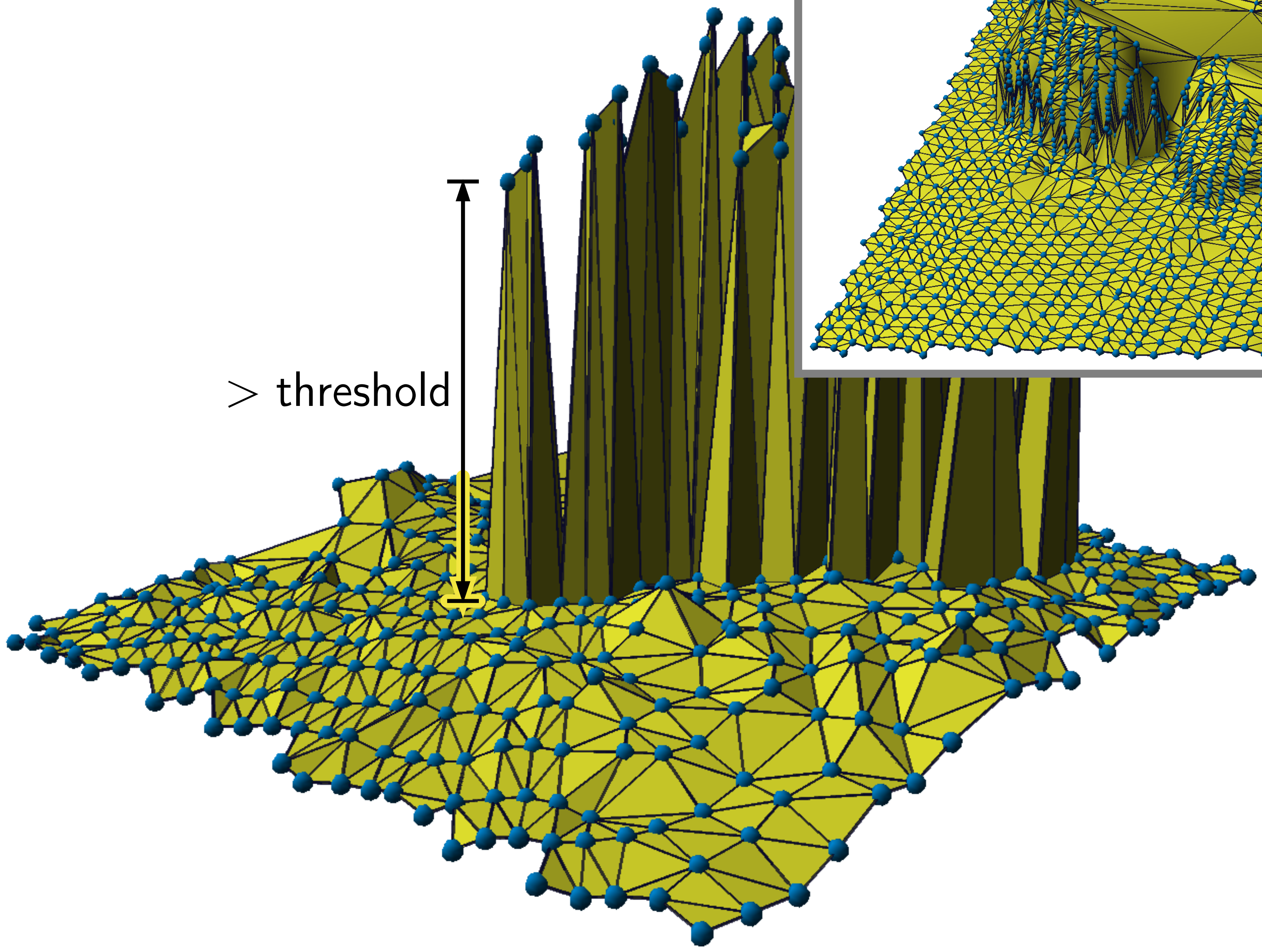

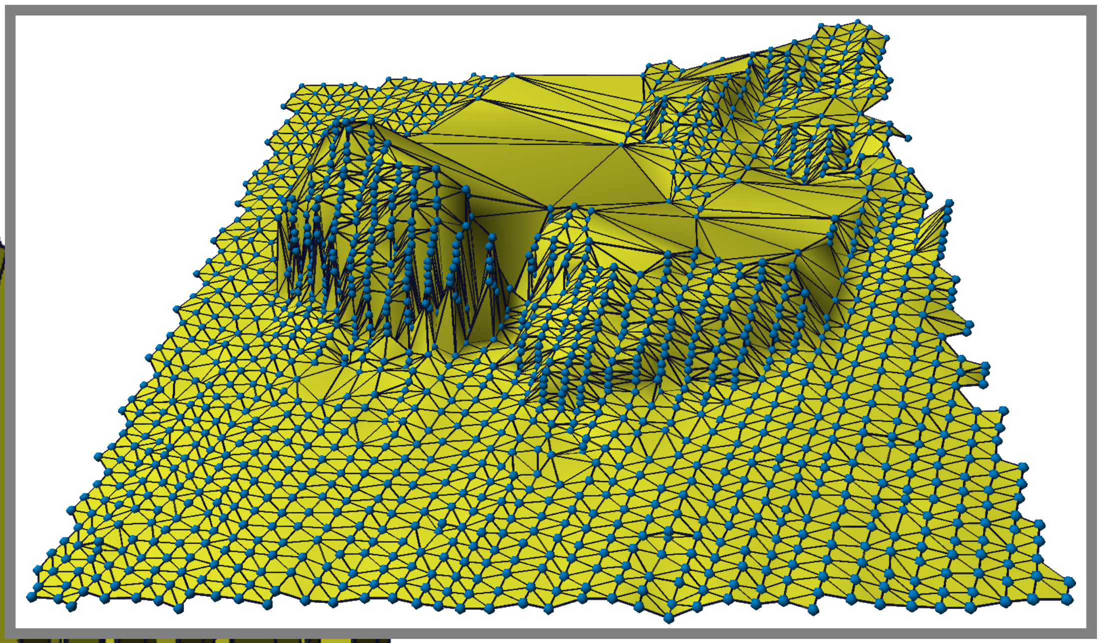

Why it works

no diagonals $\Rightarrow$ pipeline disconnected

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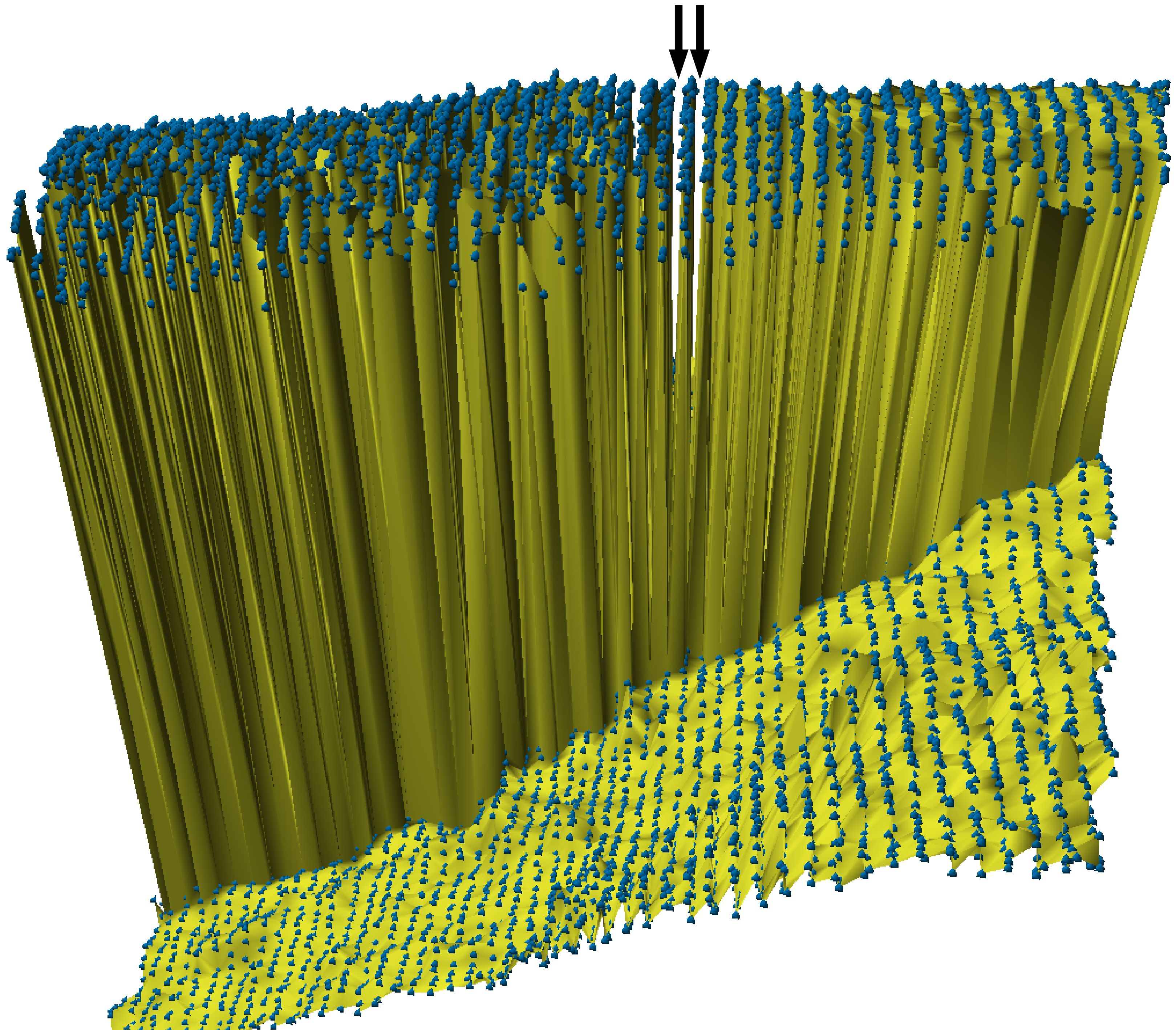

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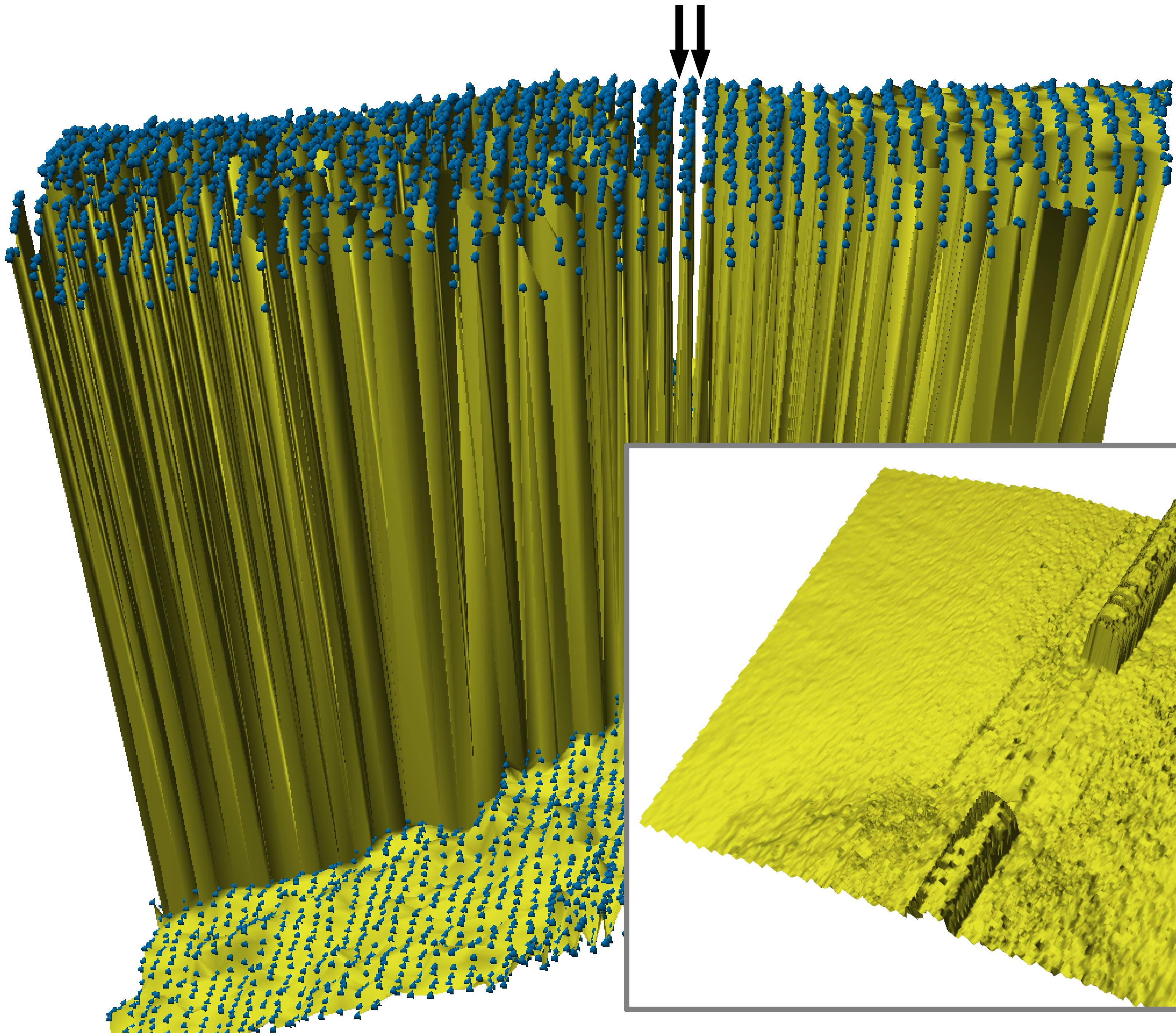
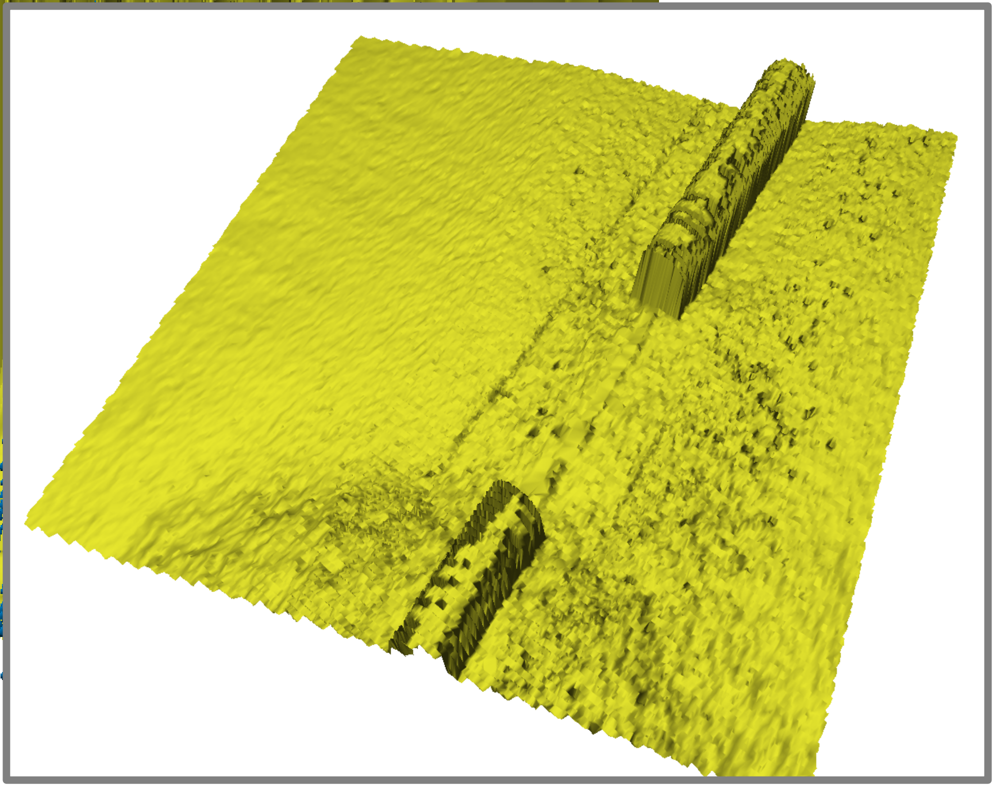
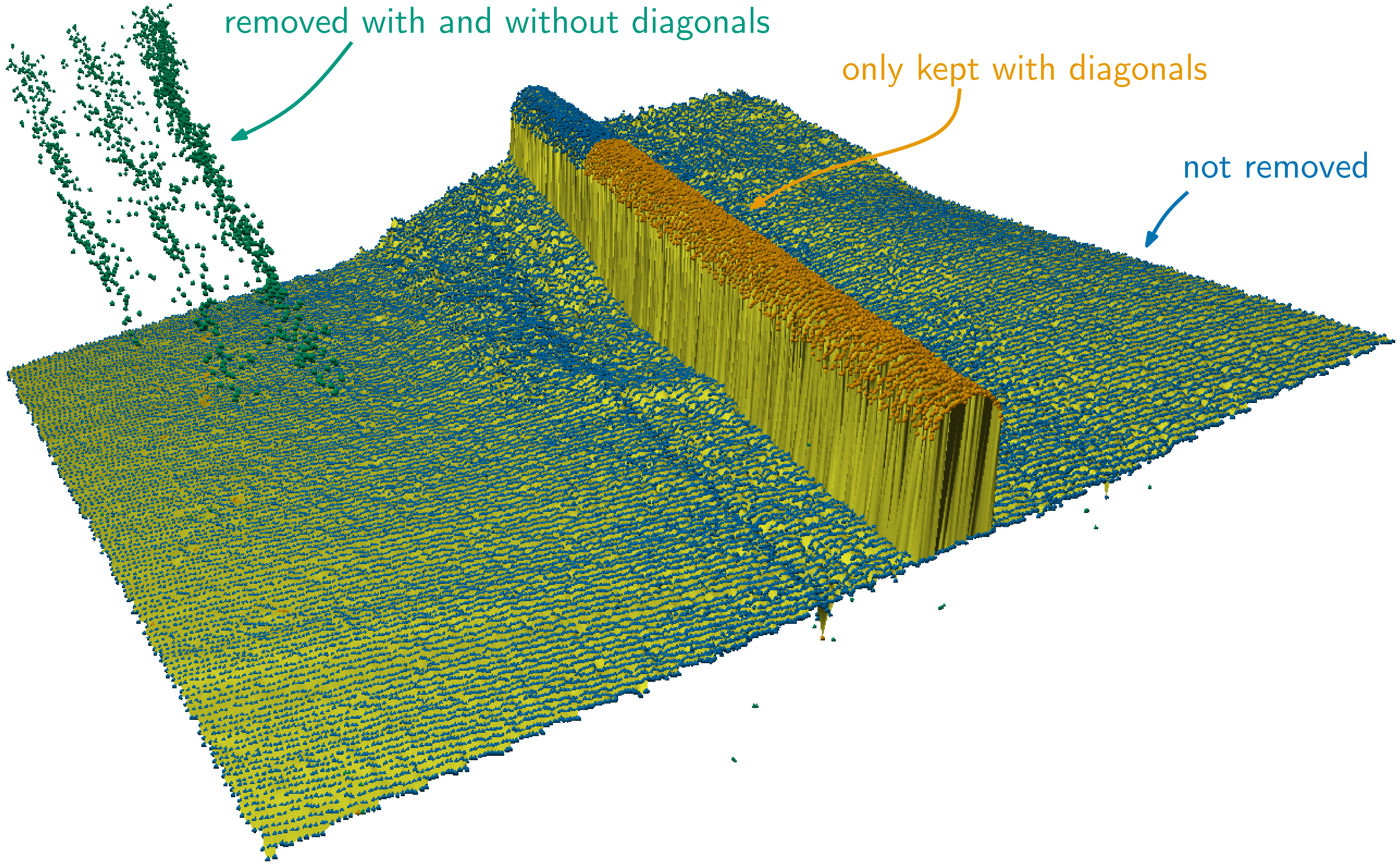




Why it works
with vs. without diagonals

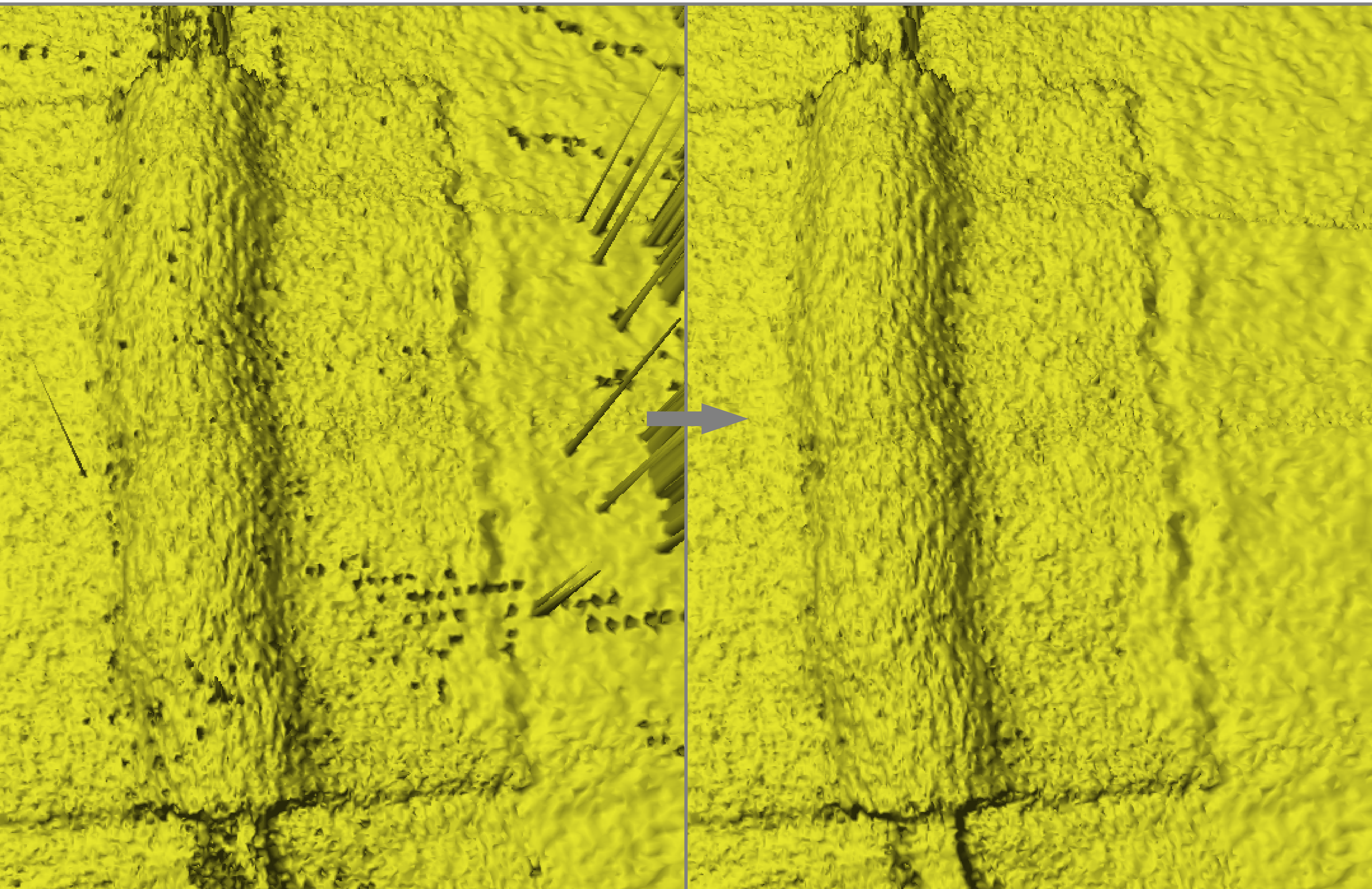
Data: StatoilHydro



Results

type-1 noise

Data: EIVA



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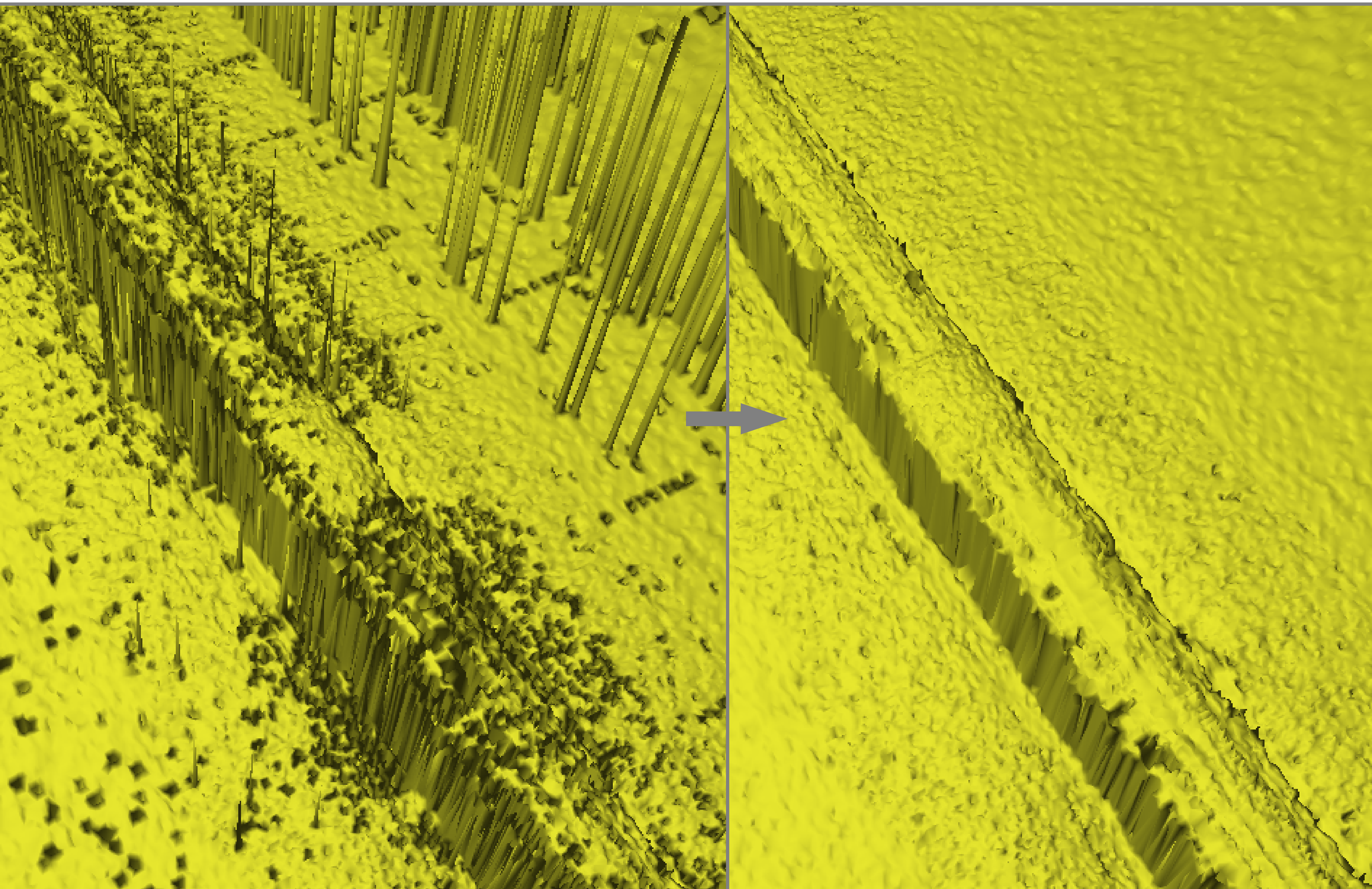
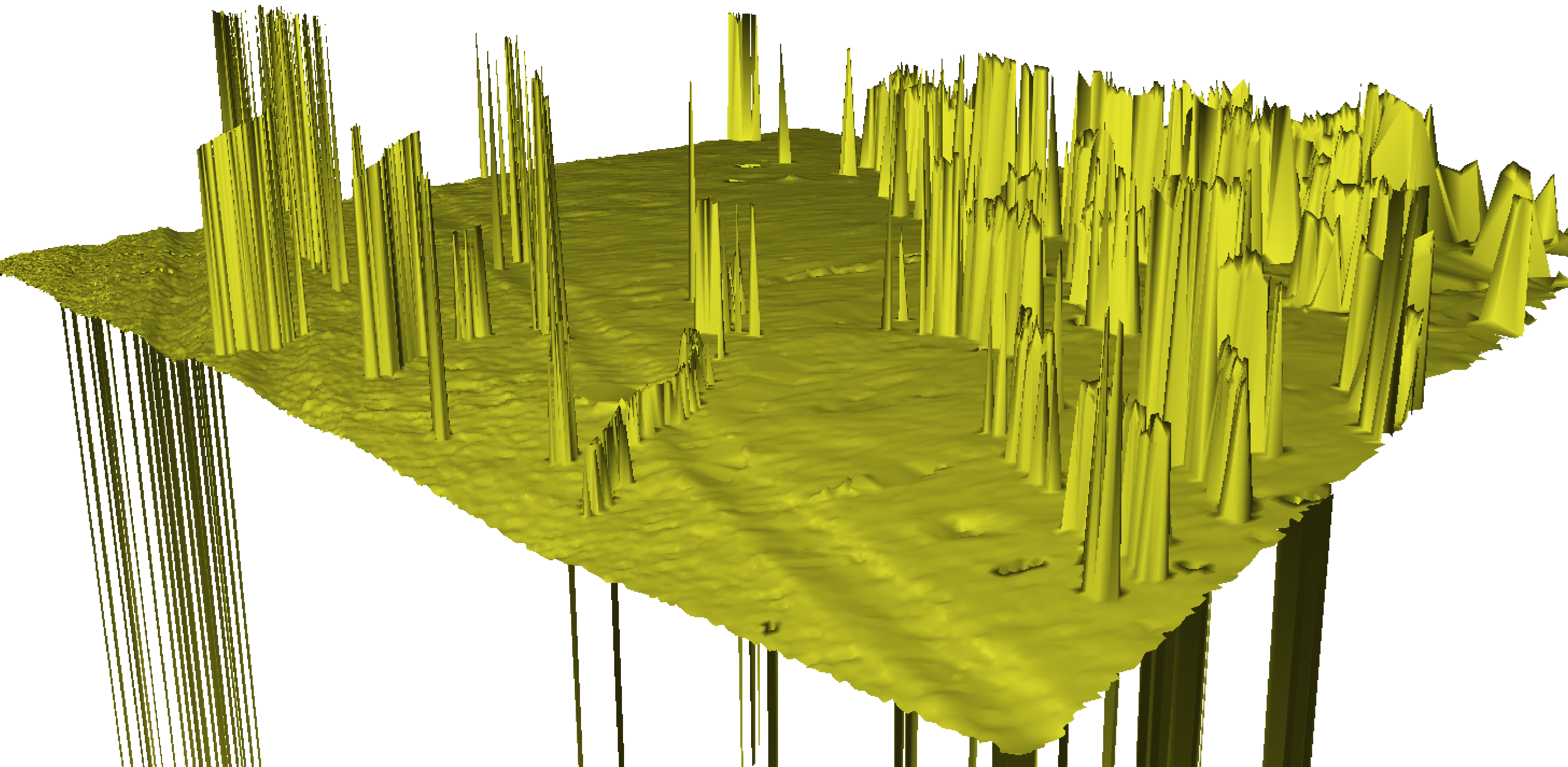


Results
type-2 noise

Data: StatoilHydro



Results

type-2 noise

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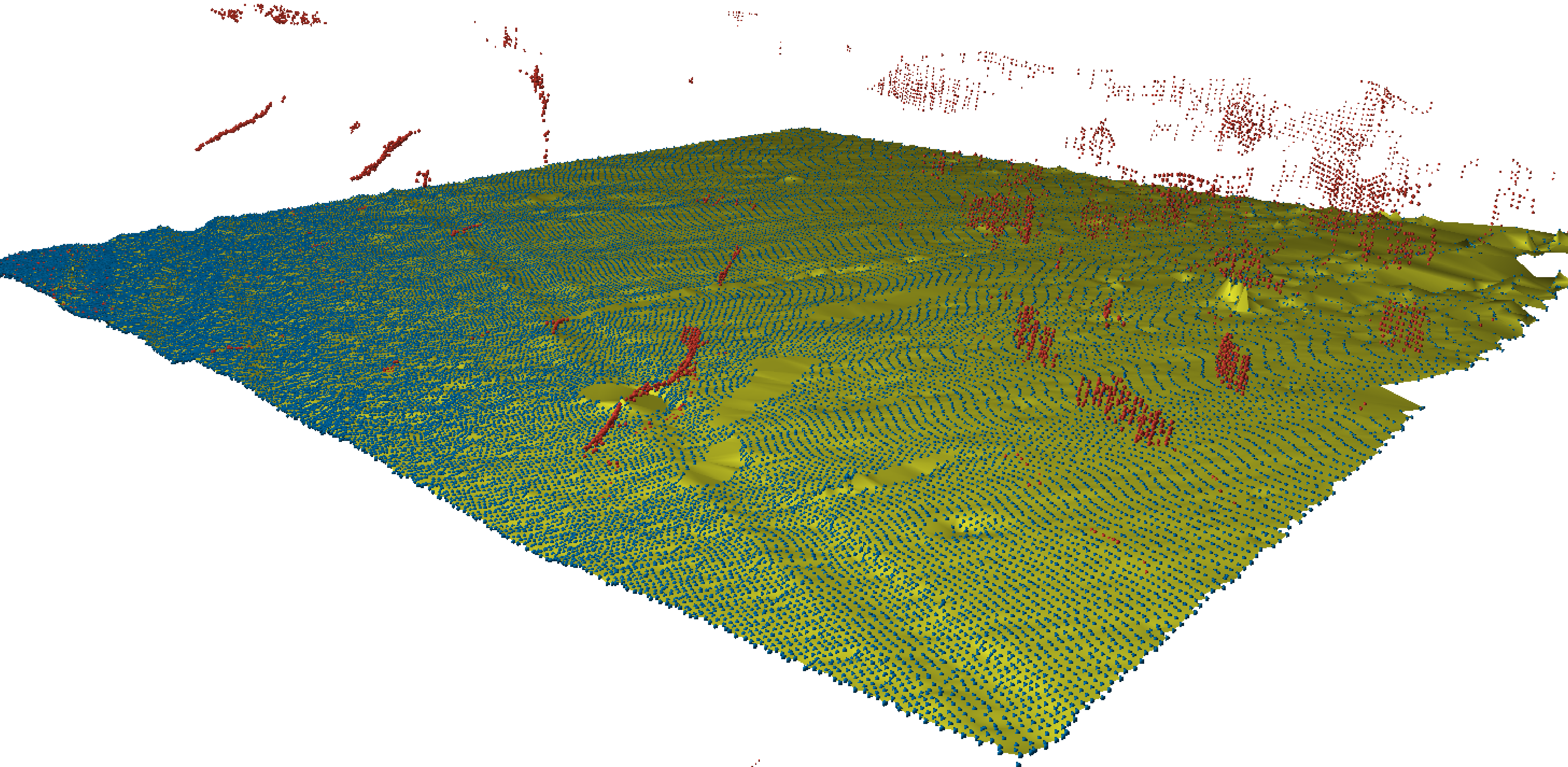
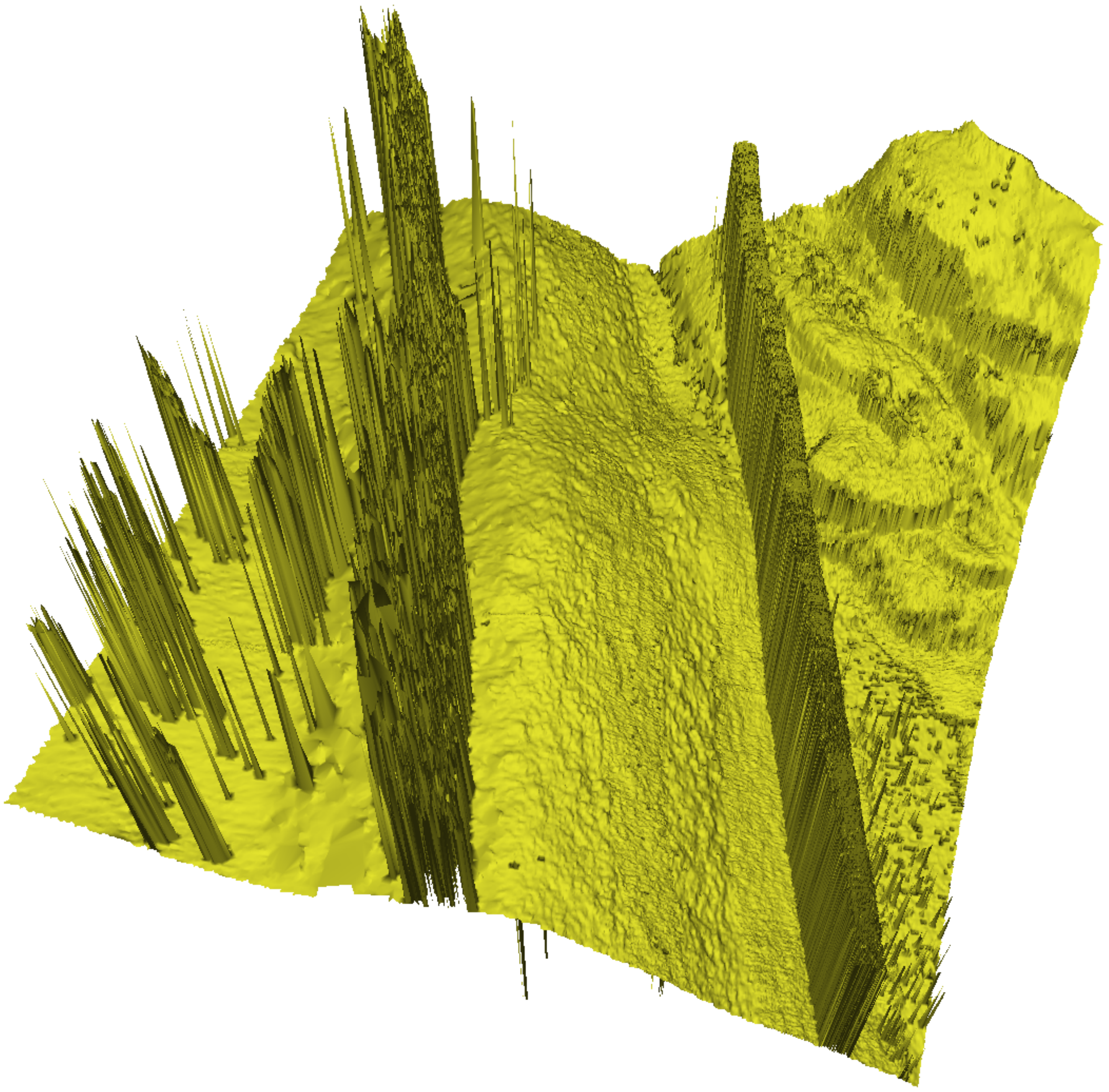


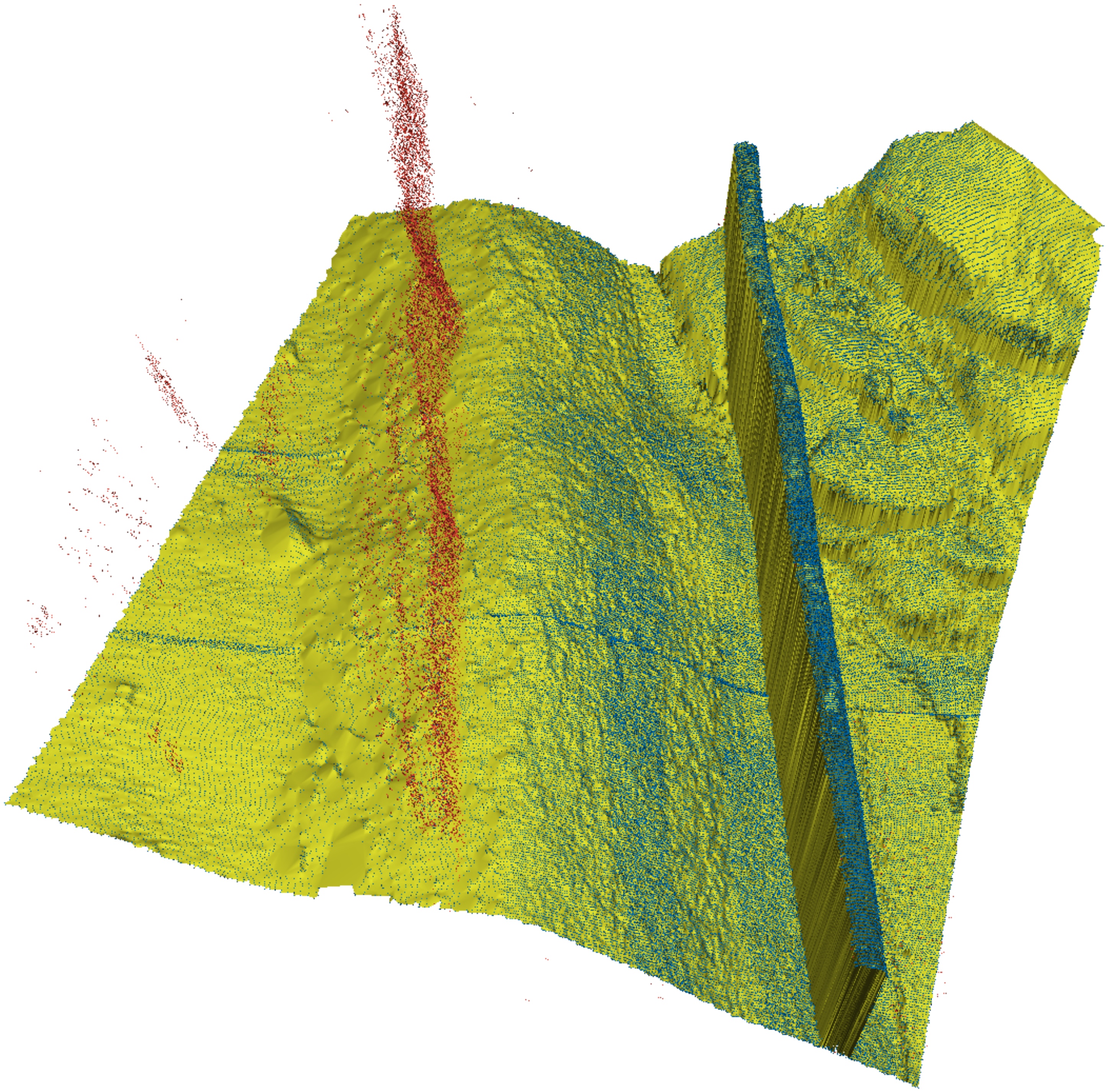
Results
type-3 noise

Data: StatoilHydro



Results
type-3 noise

Data: StatoilHydro



Results
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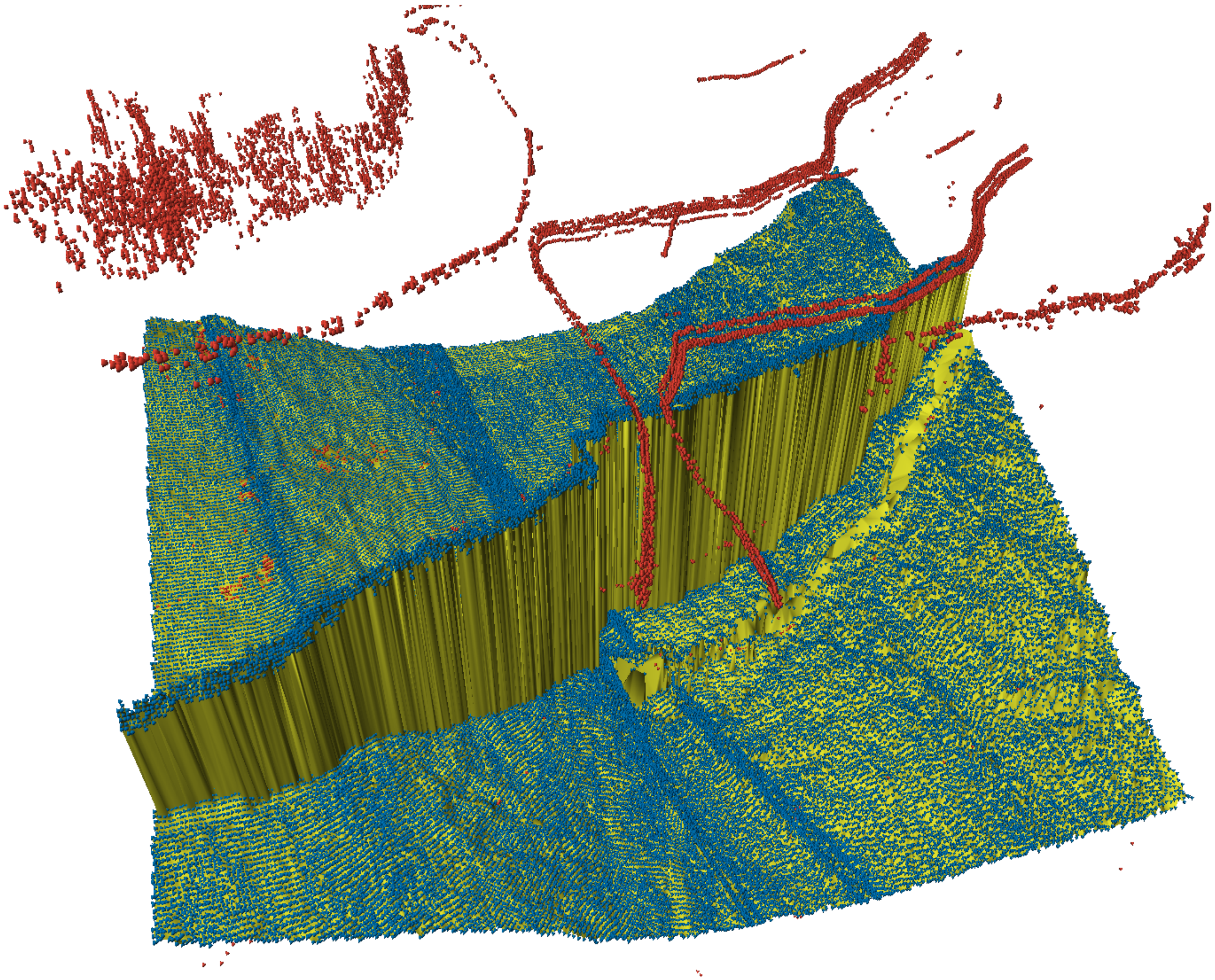
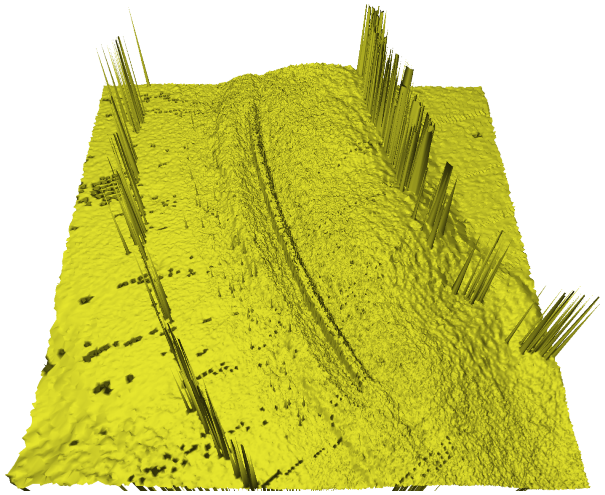
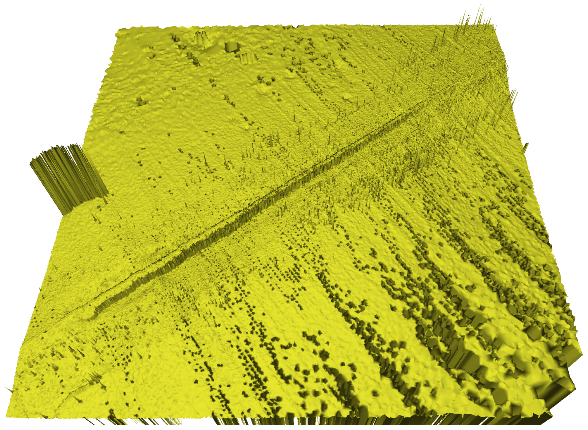
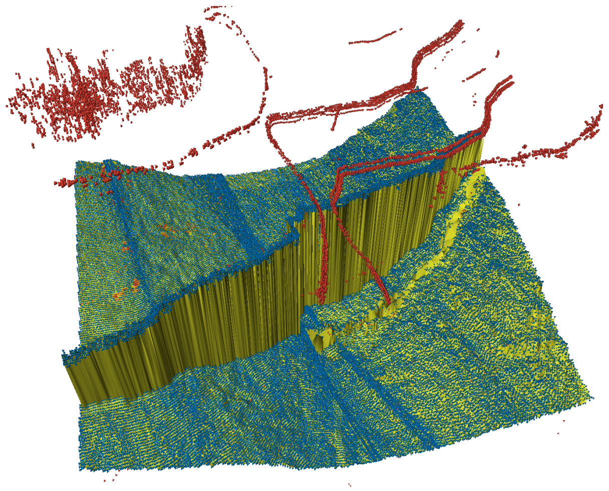
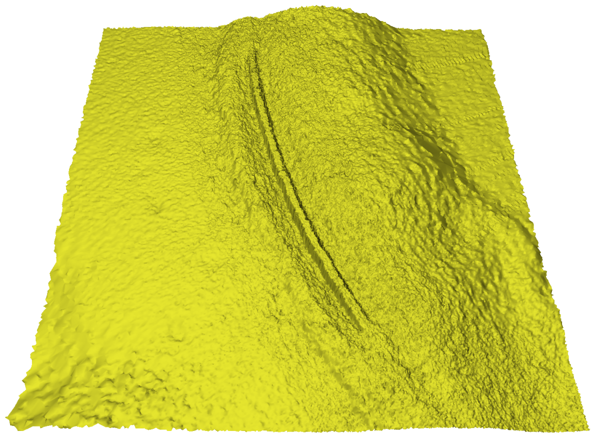
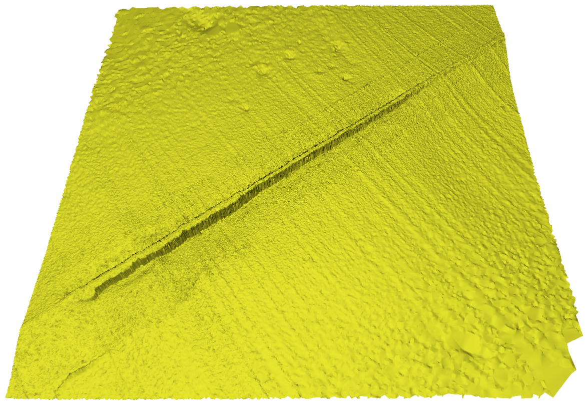


Some numbers

Data: StatoilHydro, EIVA

Noise	little	some	much
Threshold	5 cm	5 cm	35 cm
Manually removed: not auto.	0.4%	13%	18%
Not manual. removed: only auto.	0.4%	0.3%	0.8%

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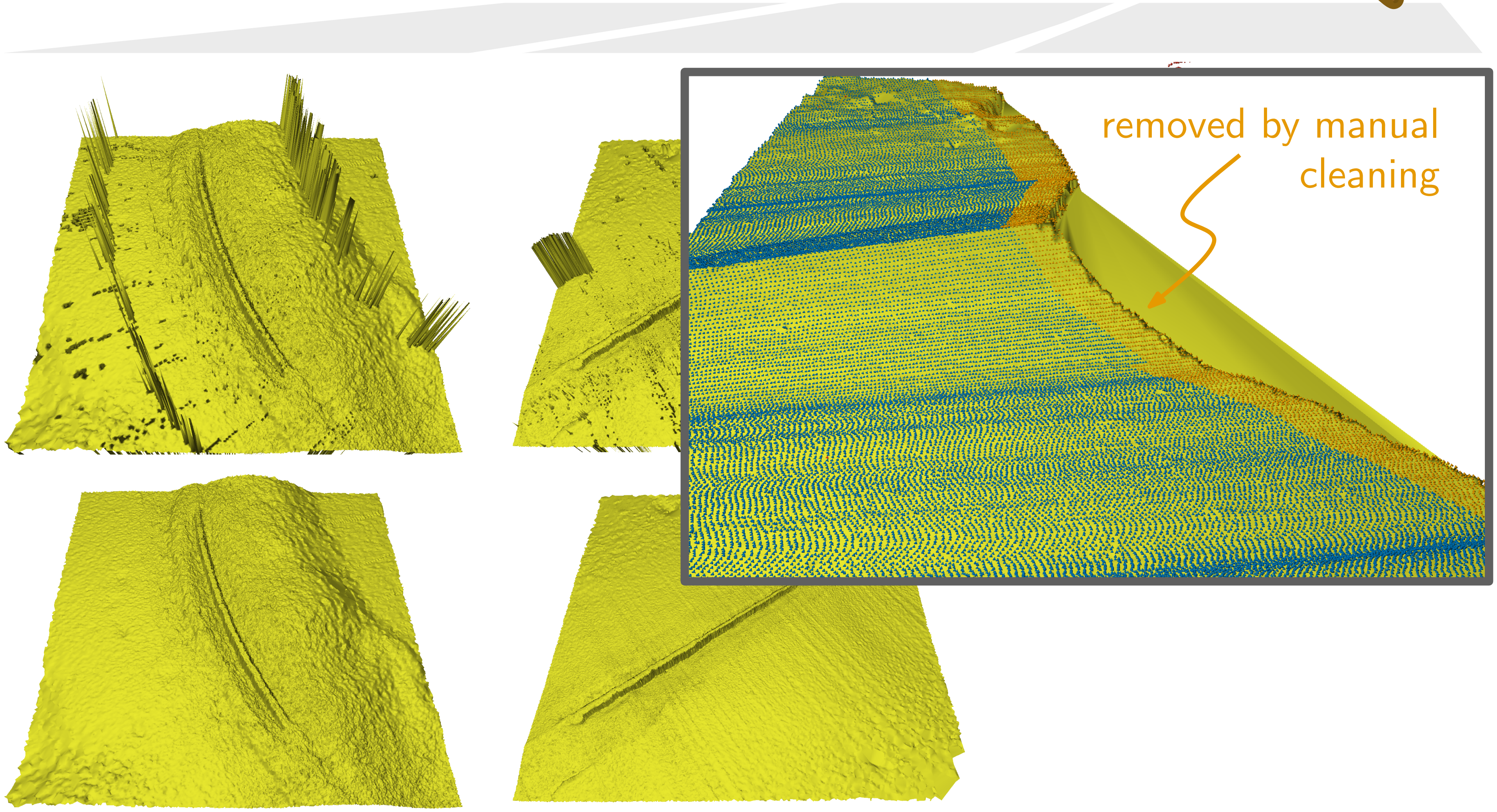

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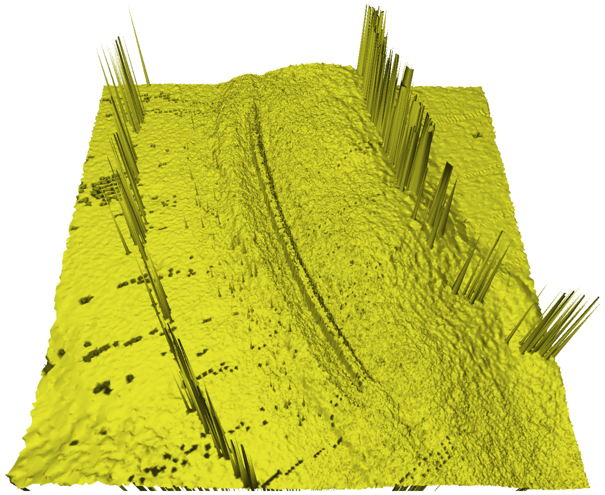
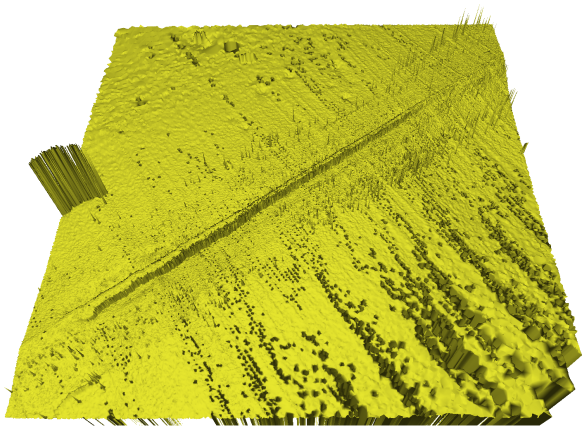
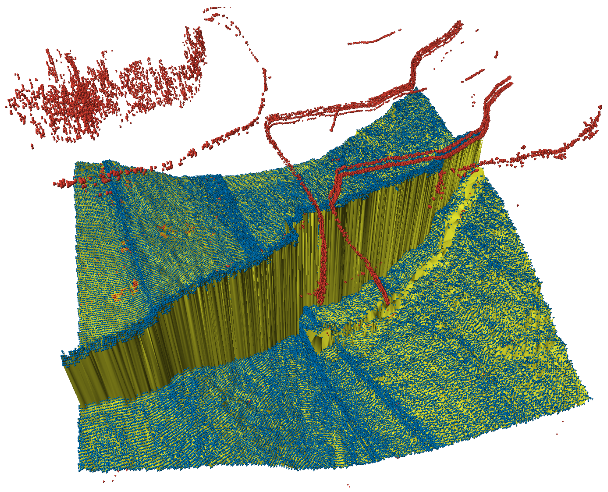
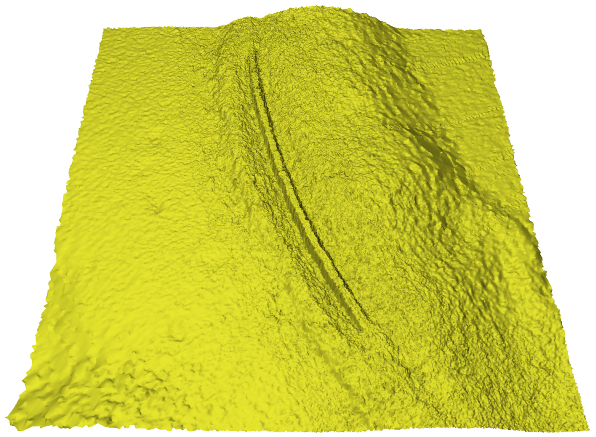
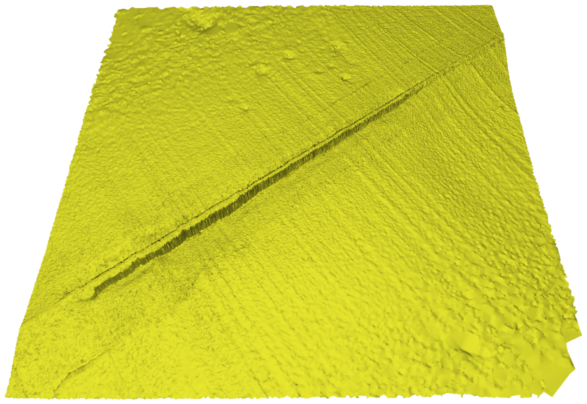

Conclusion, future work

Implemented in commercial product

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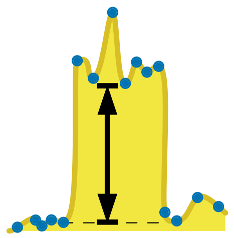
Implemented in commercial product

- Open problem: defining theoretical model of outlier noise
  - Objective theoretical performance analysis
  - Compare Delaunay triangulation with other neighbourhood graphs



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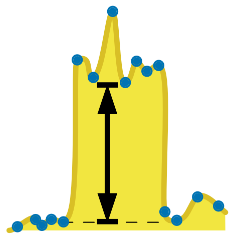
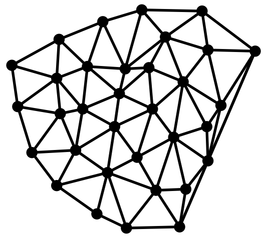


- Open problem: find easier alternative to Delaunay triangulation
  Requirements:
  - Good connectivity
  - Fast to compute



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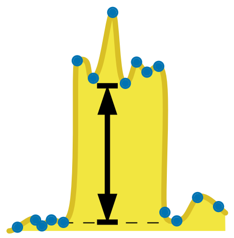

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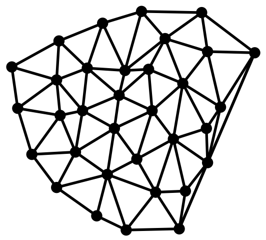
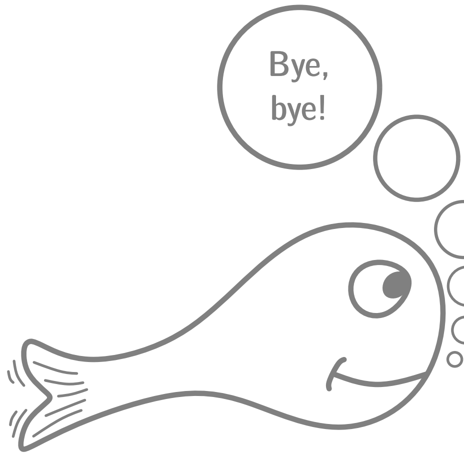
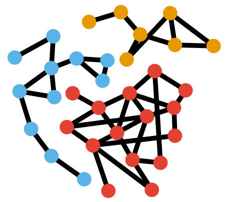


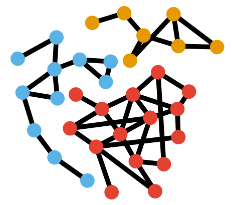


Connected component algorithm



- Compute connected component labelling:
  vertices have equal labels $\Leftrightarrow$ they are in the same connected component

Connected component algorithm



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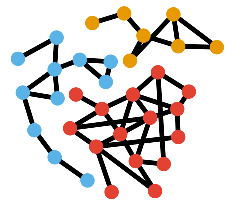
- Algorithm: two phases, sweeping over edge & vertex lists
  - *Down phase*: augment some vertices with additional connectivity info.
  - *Up phase*: compute final component labels

  Assumption: edges intersecting sweep line always fit in main memory

Connected component algorithm



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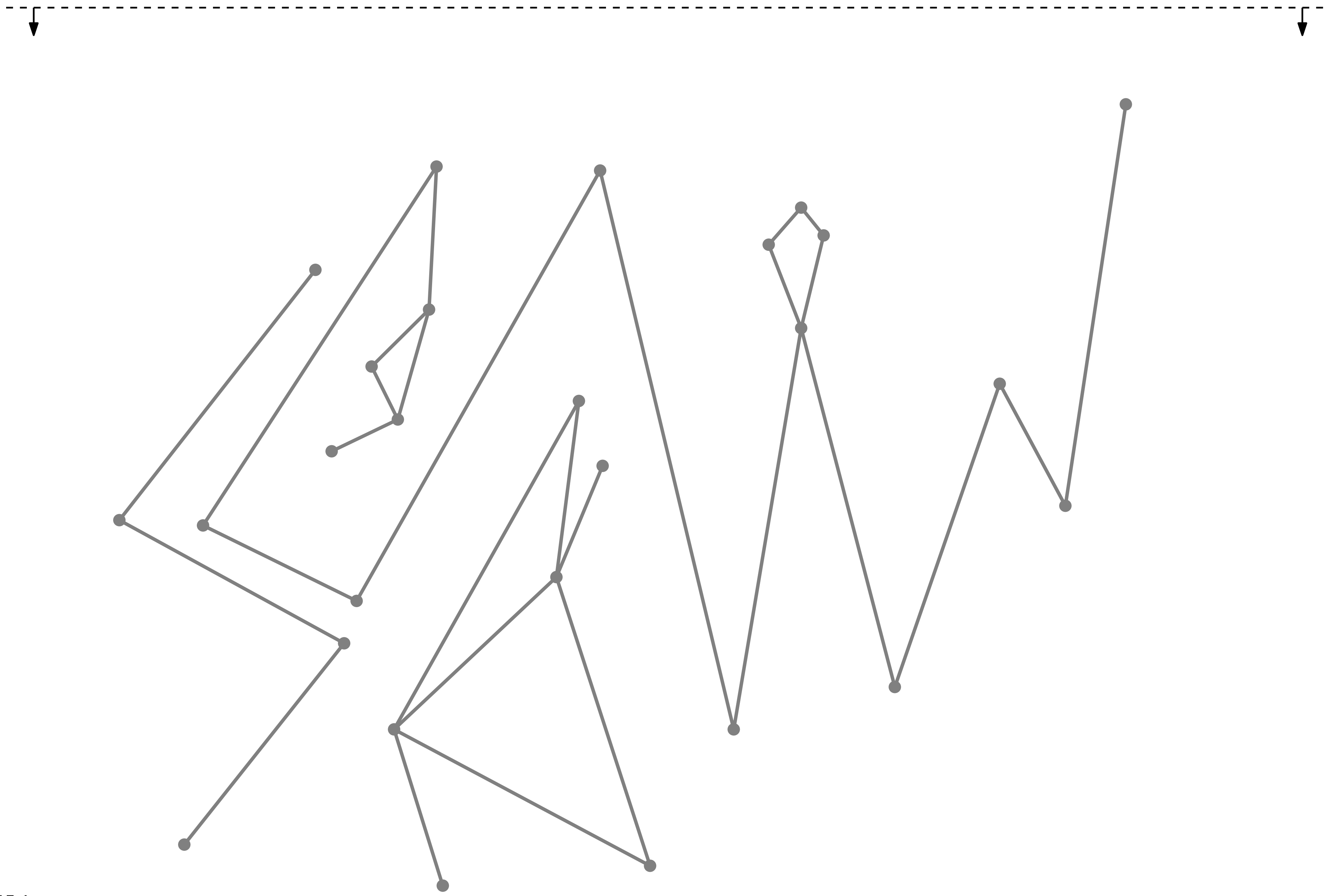
- Total number of I/Os necessary: $O(\mathtt{sort}(N))$

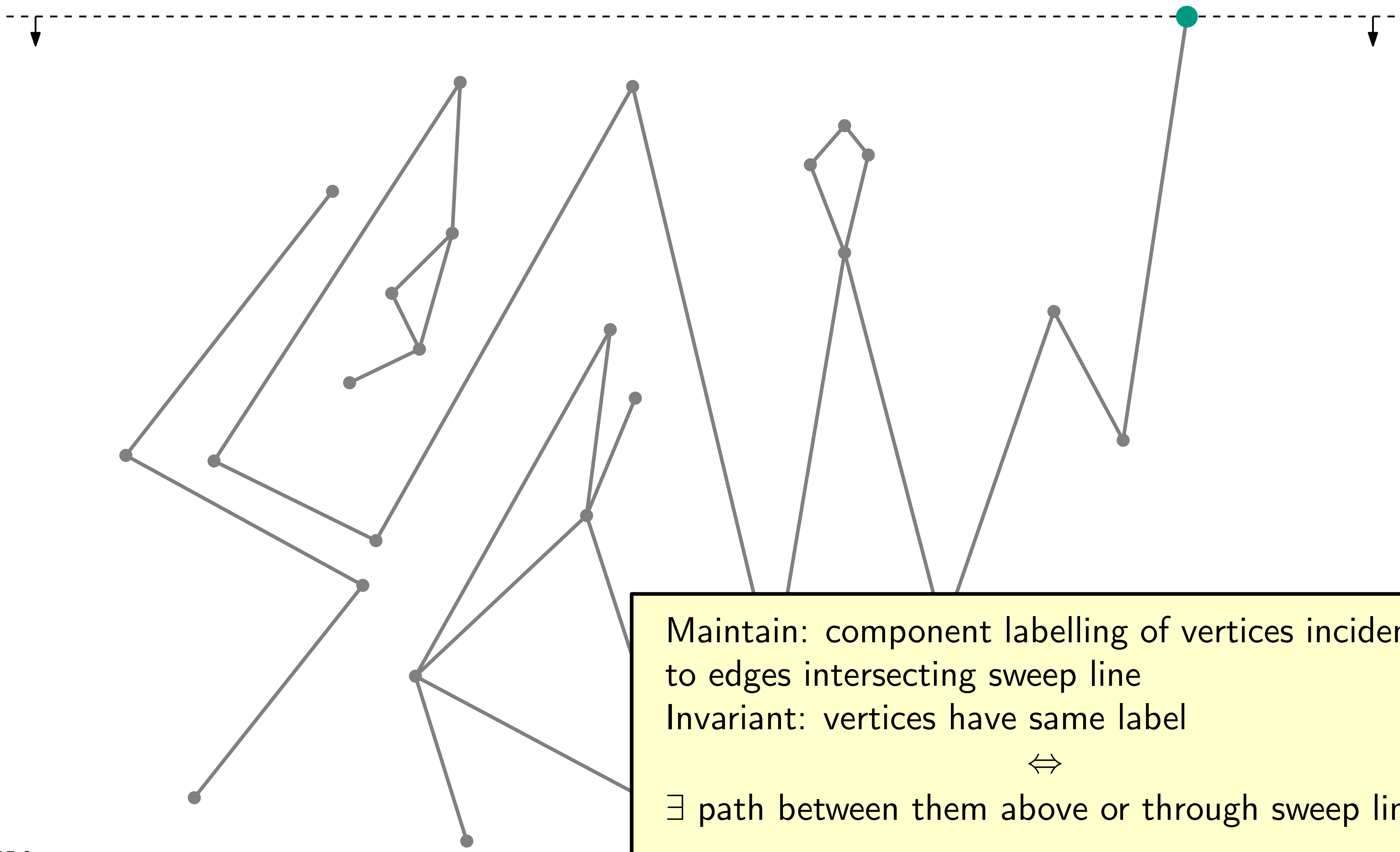
Connected component algorithm

down phase



Connected component algorithm

down phase



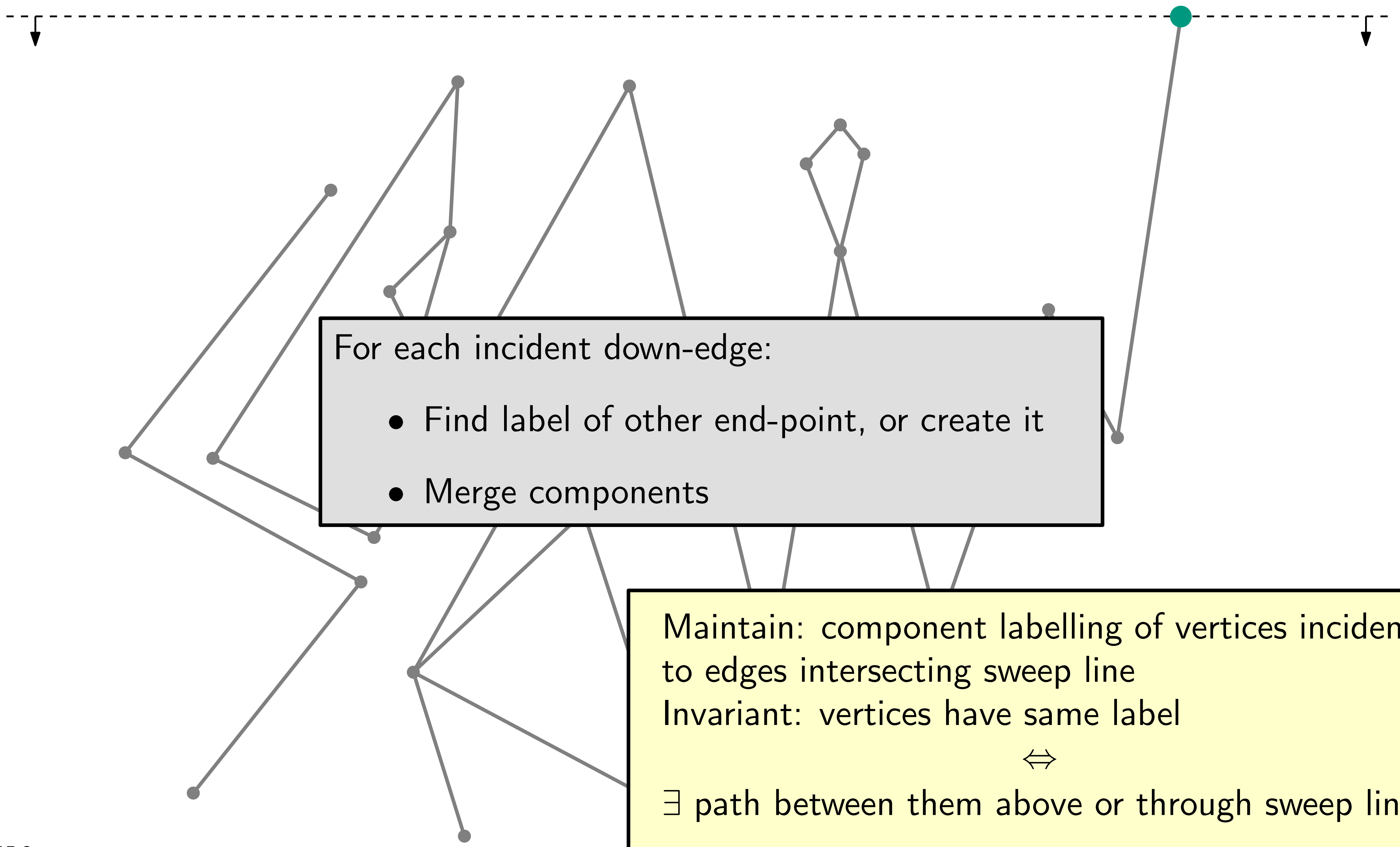
Maintain: component labelling of vertices incident to edges intersecting sweep line

Invariant: vertices have same label

$$\Leftrightarrow$$

$\exists$ path between them above or through sweep line

Connected component algorithm
down phase



For each incident down-edge:

- Find label of other end-point, or create it
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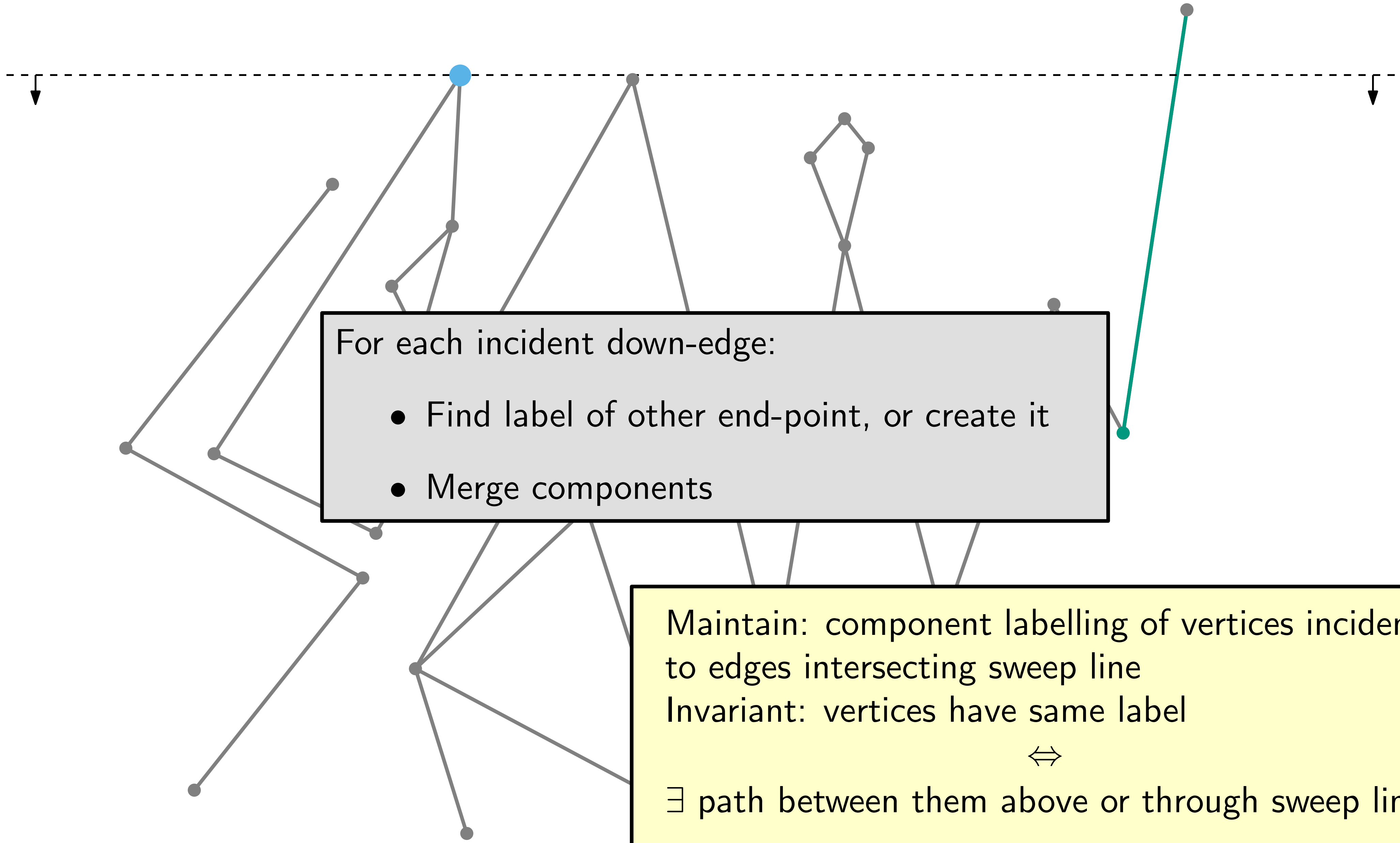

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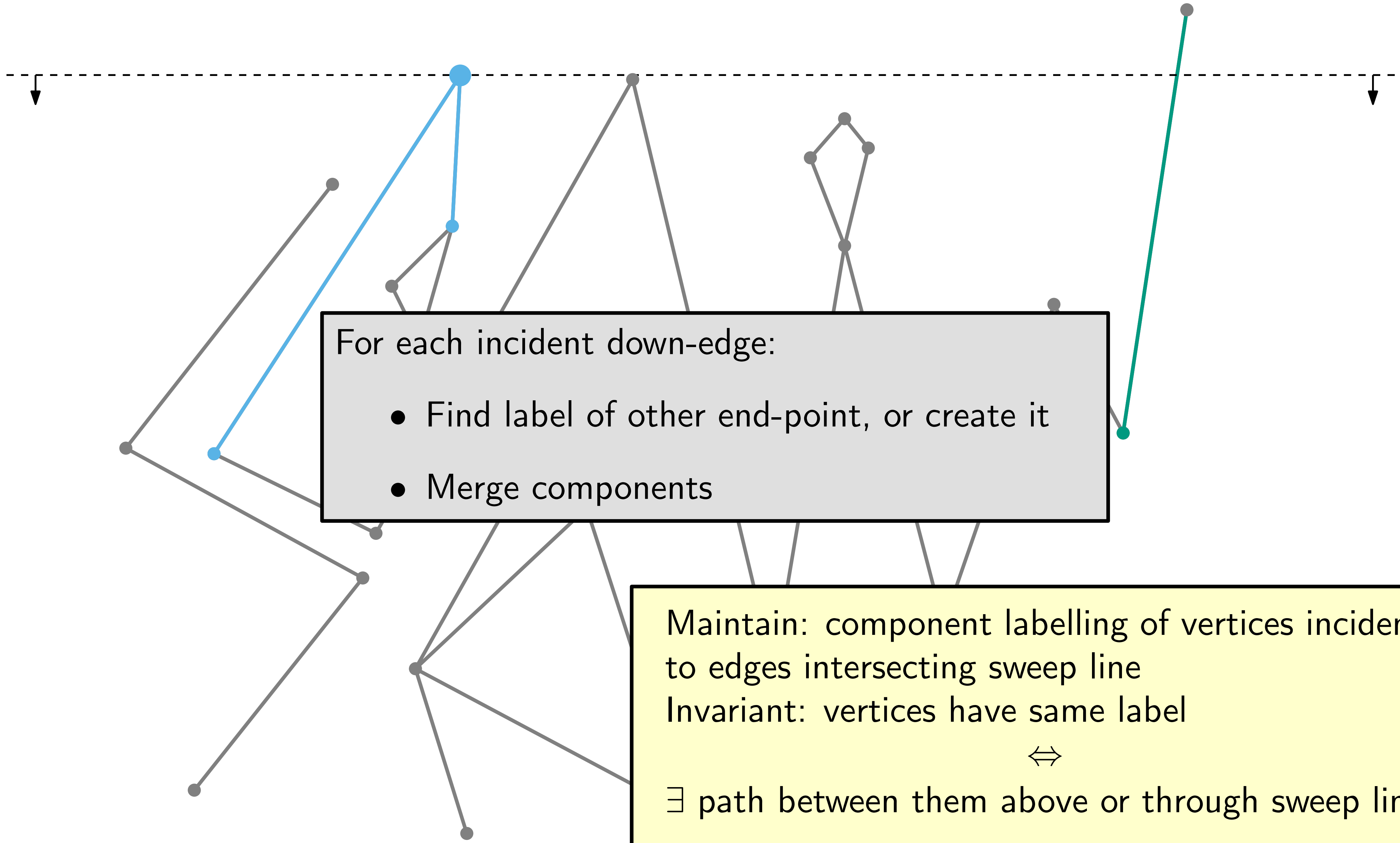

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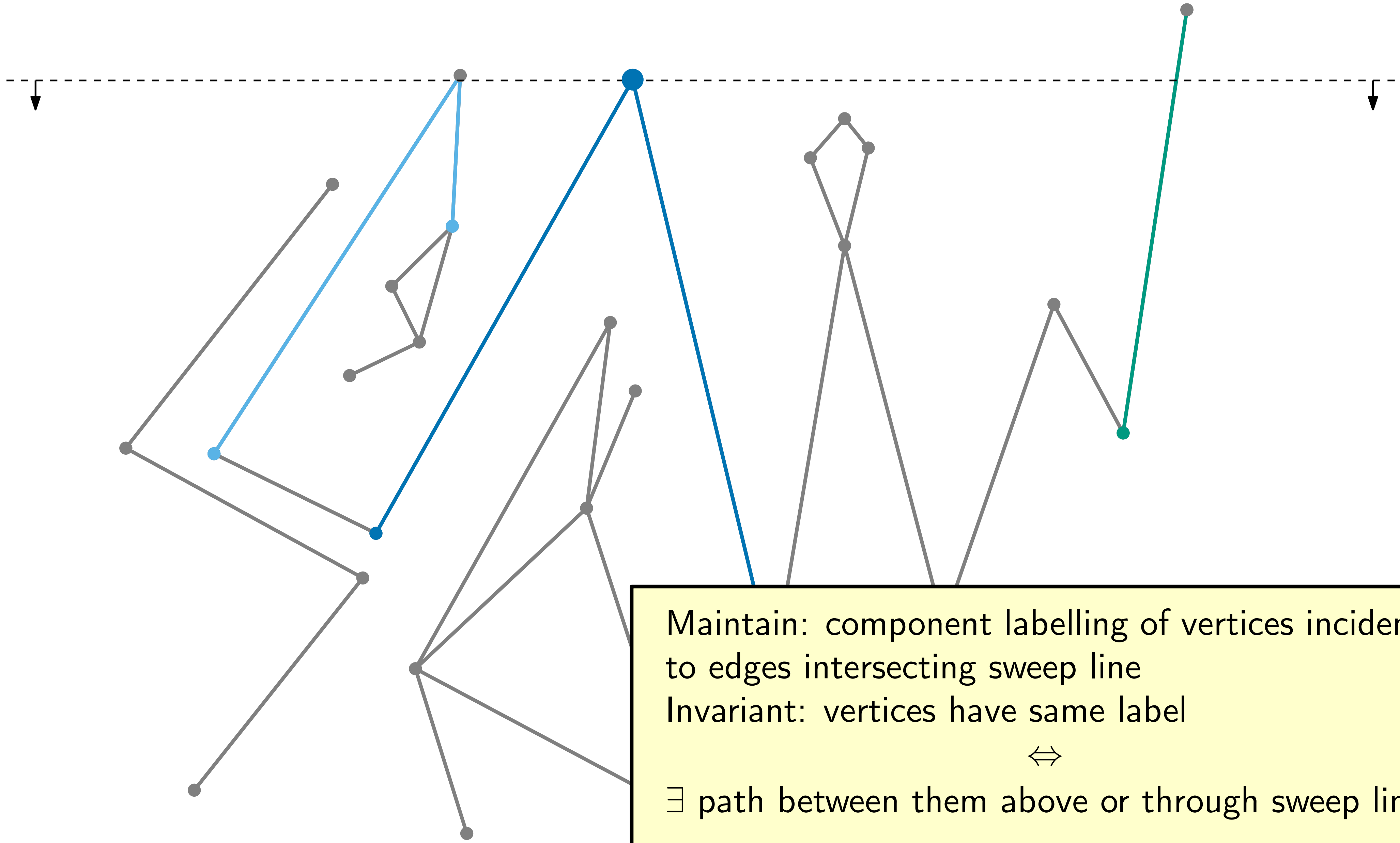

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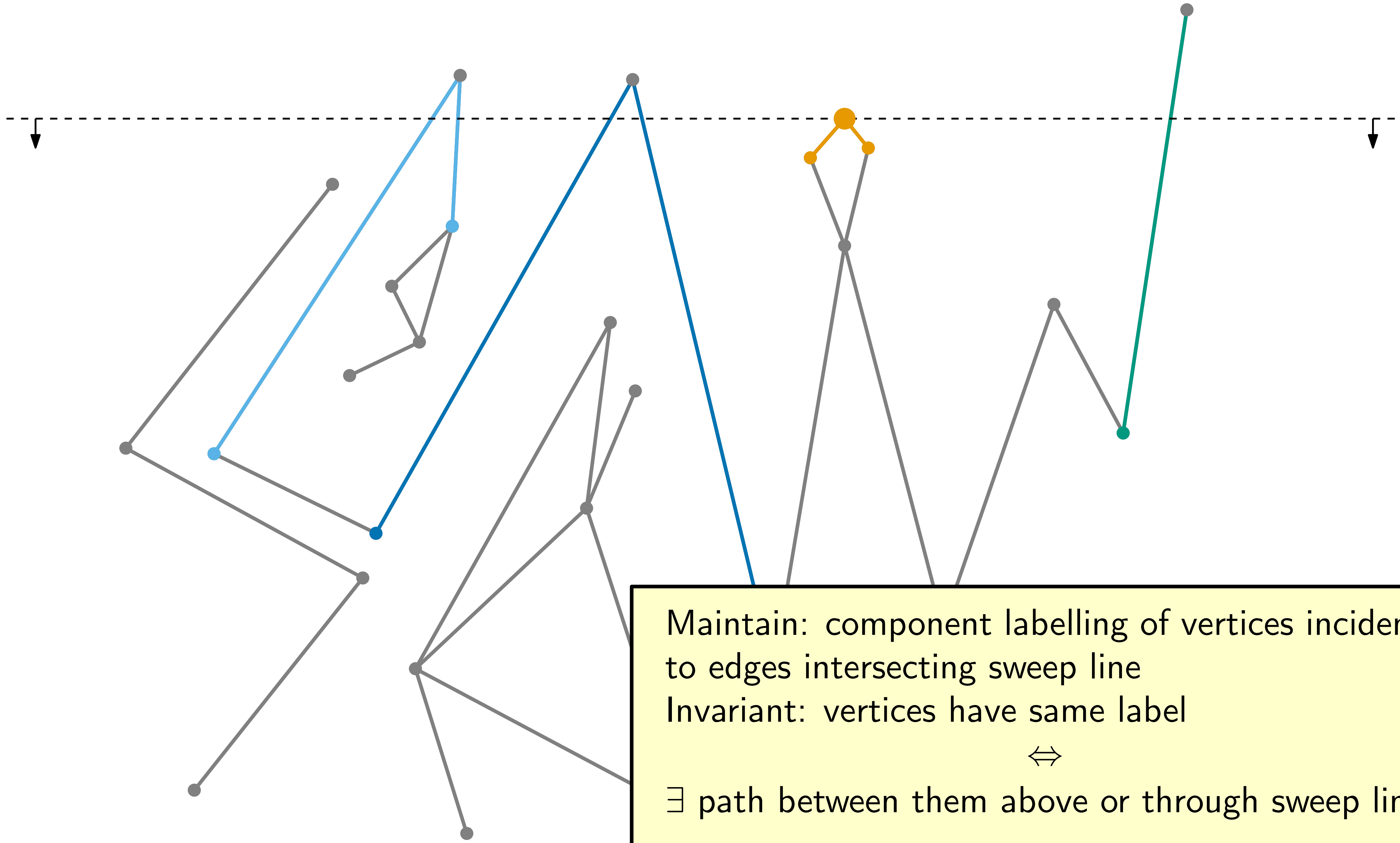

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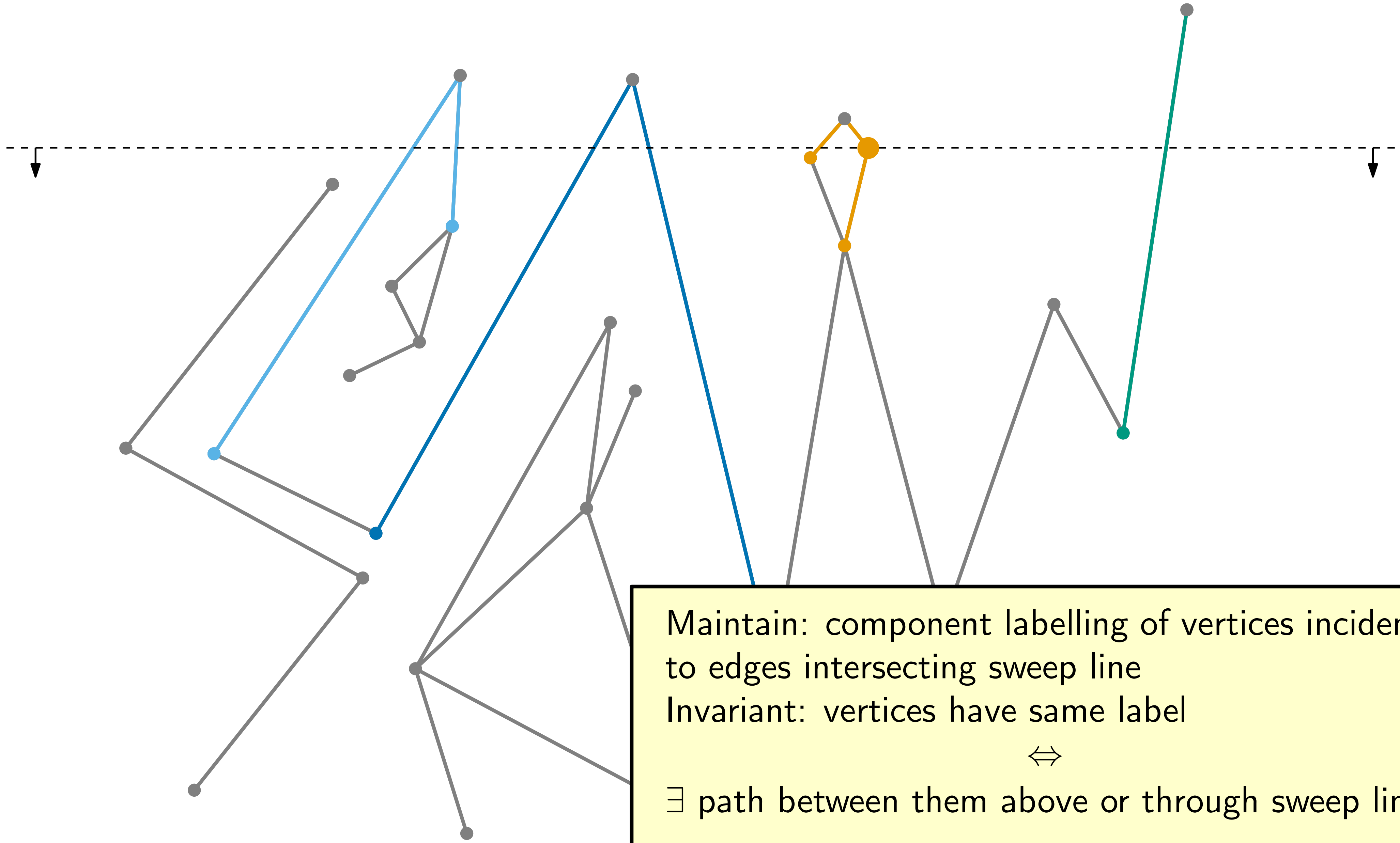

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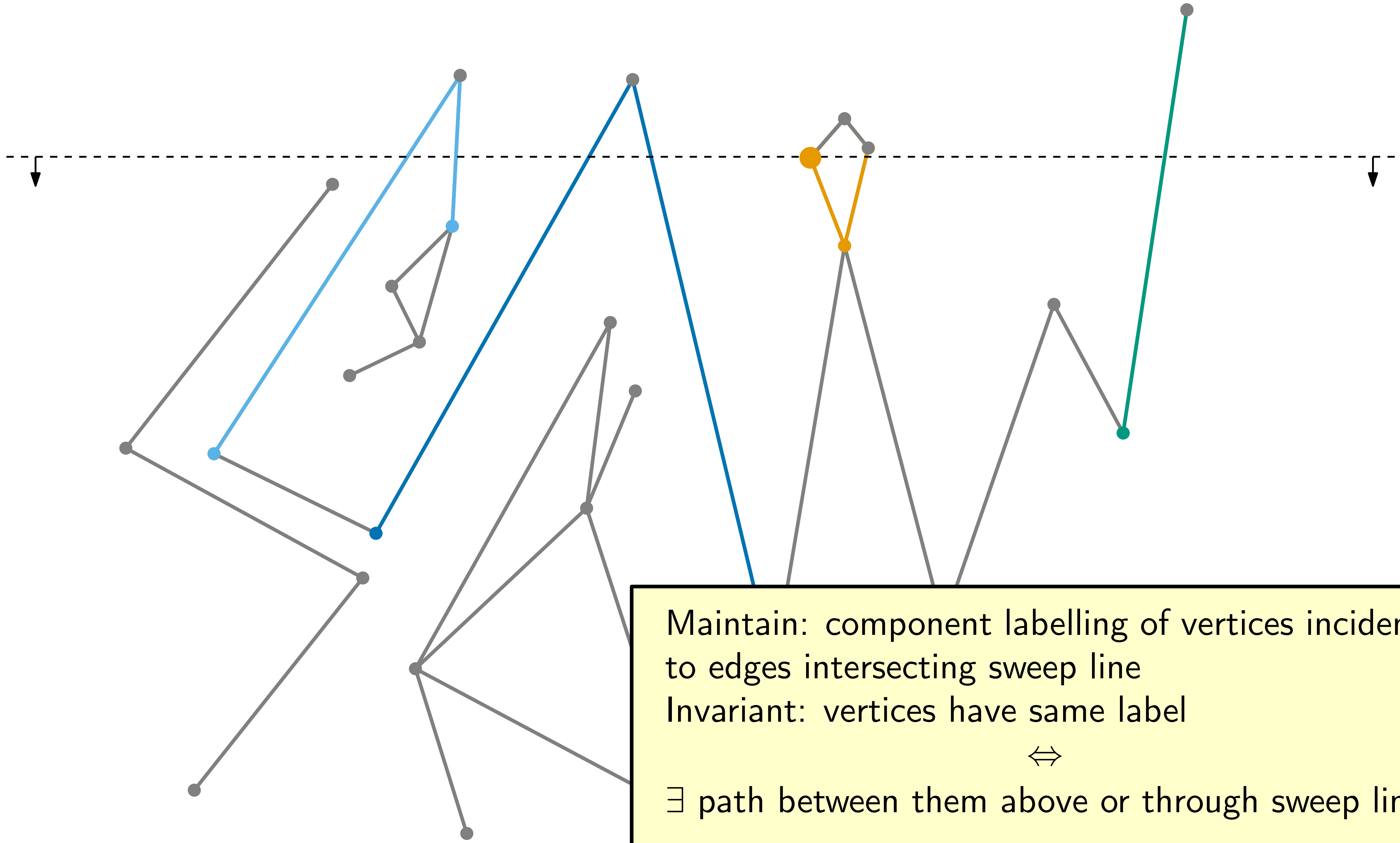

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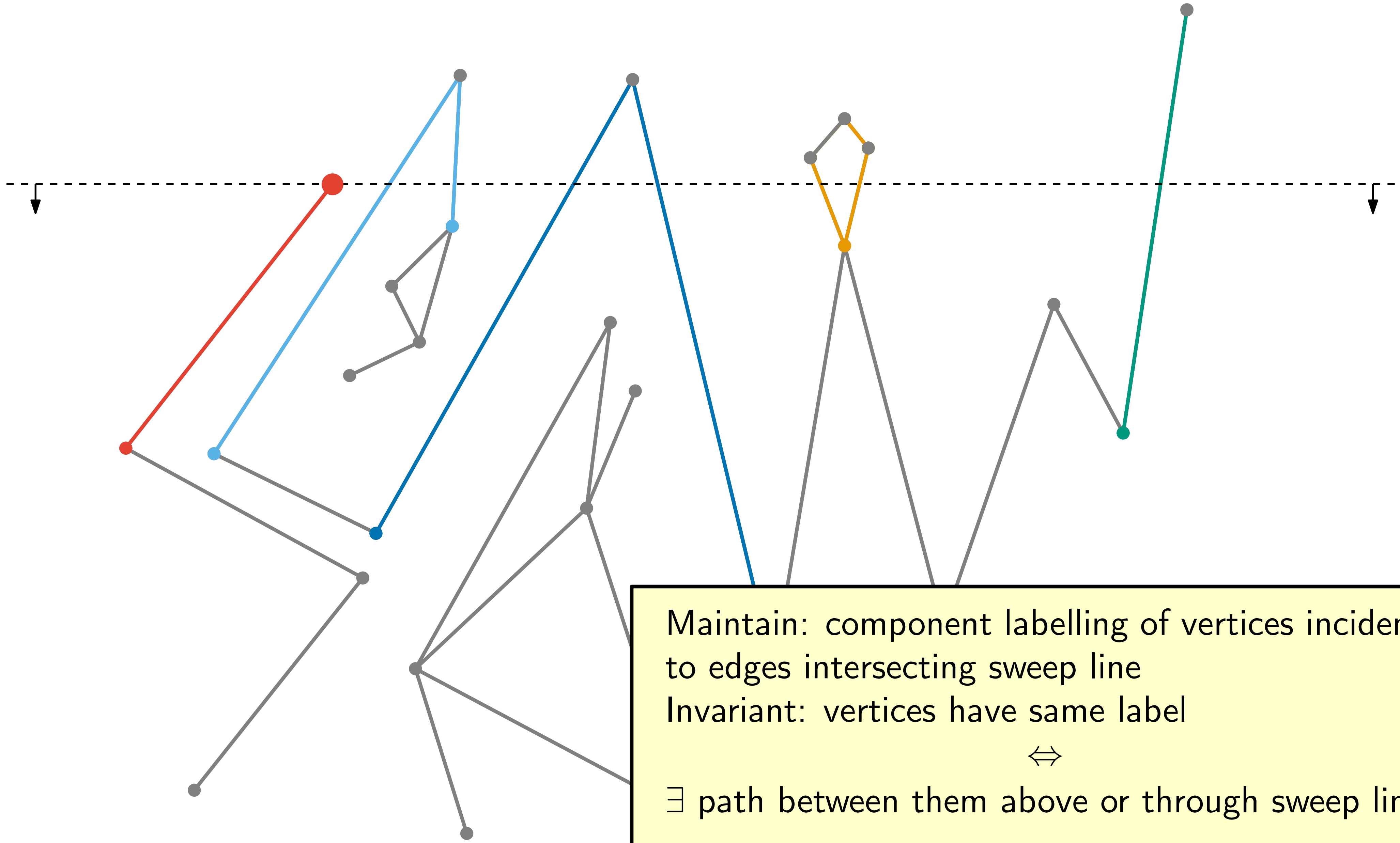

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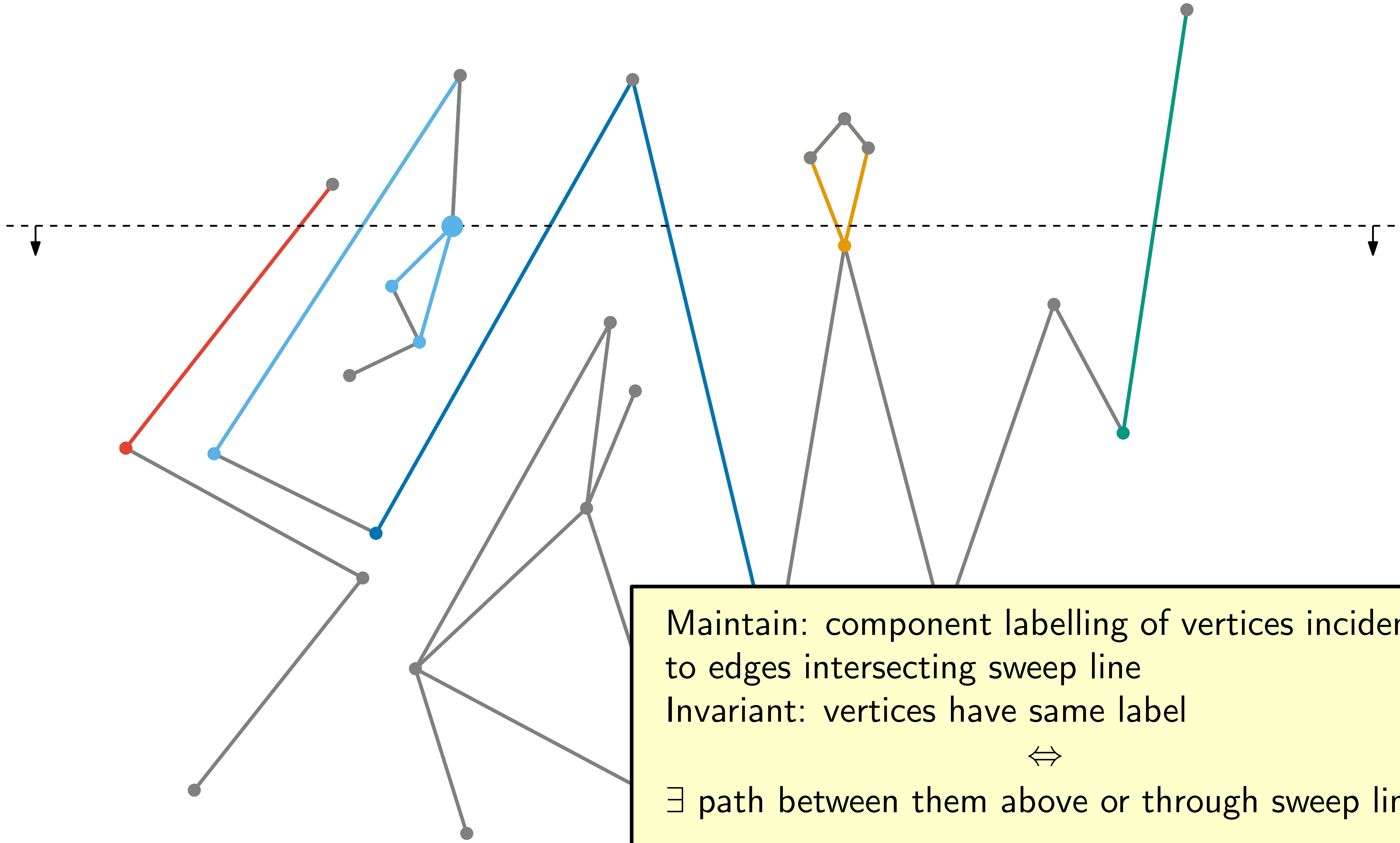
Connected component algorithm
down phase



Maintain: component labelling of vertices incident to edges intersecting sweep line
Invariant: vertices have same label

$\Leftrightarrow$

$\exists$ path between them above or through sweep line

Connected component algorithm
down phase

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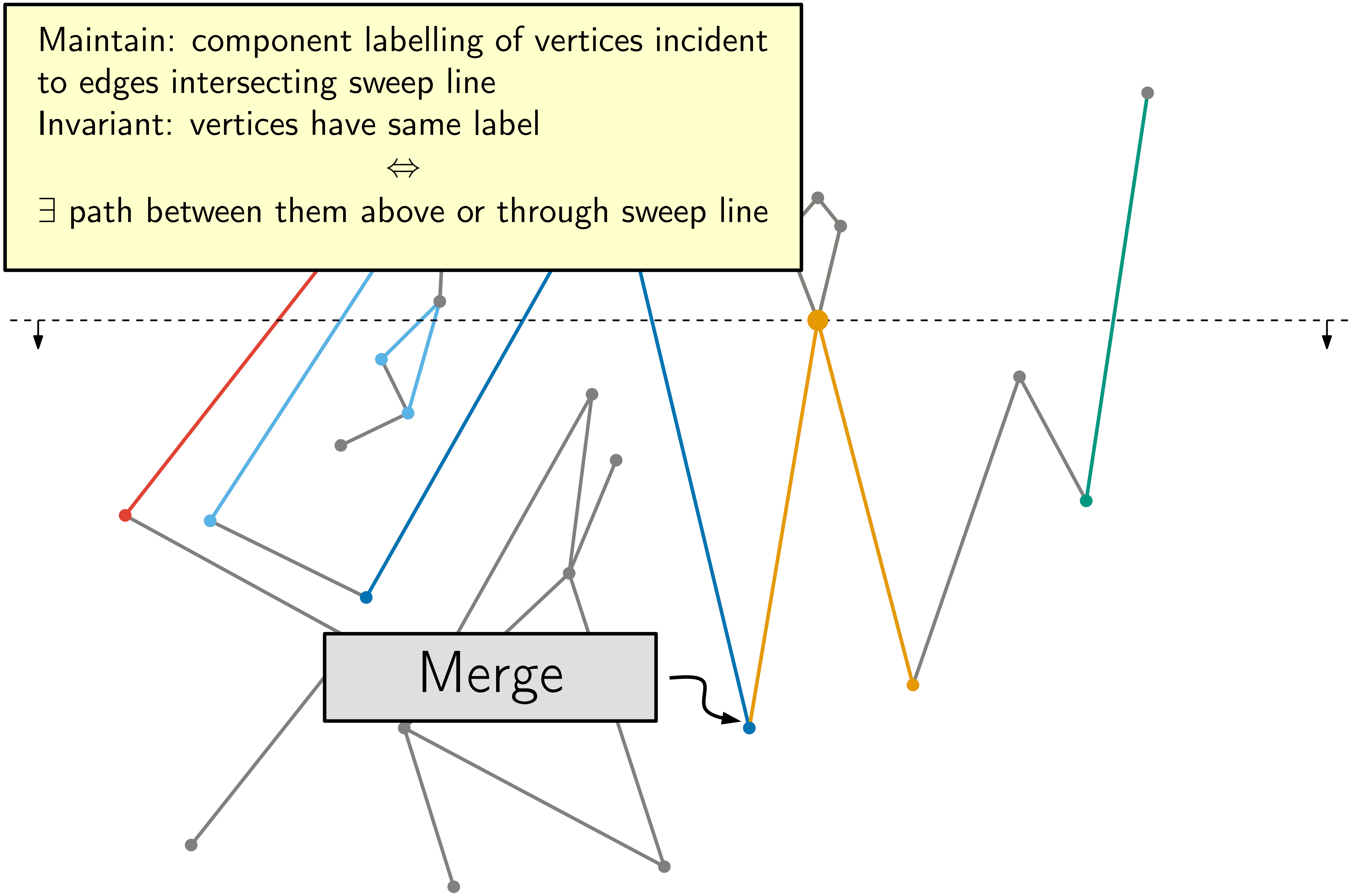

Connected component algorithm
down phase

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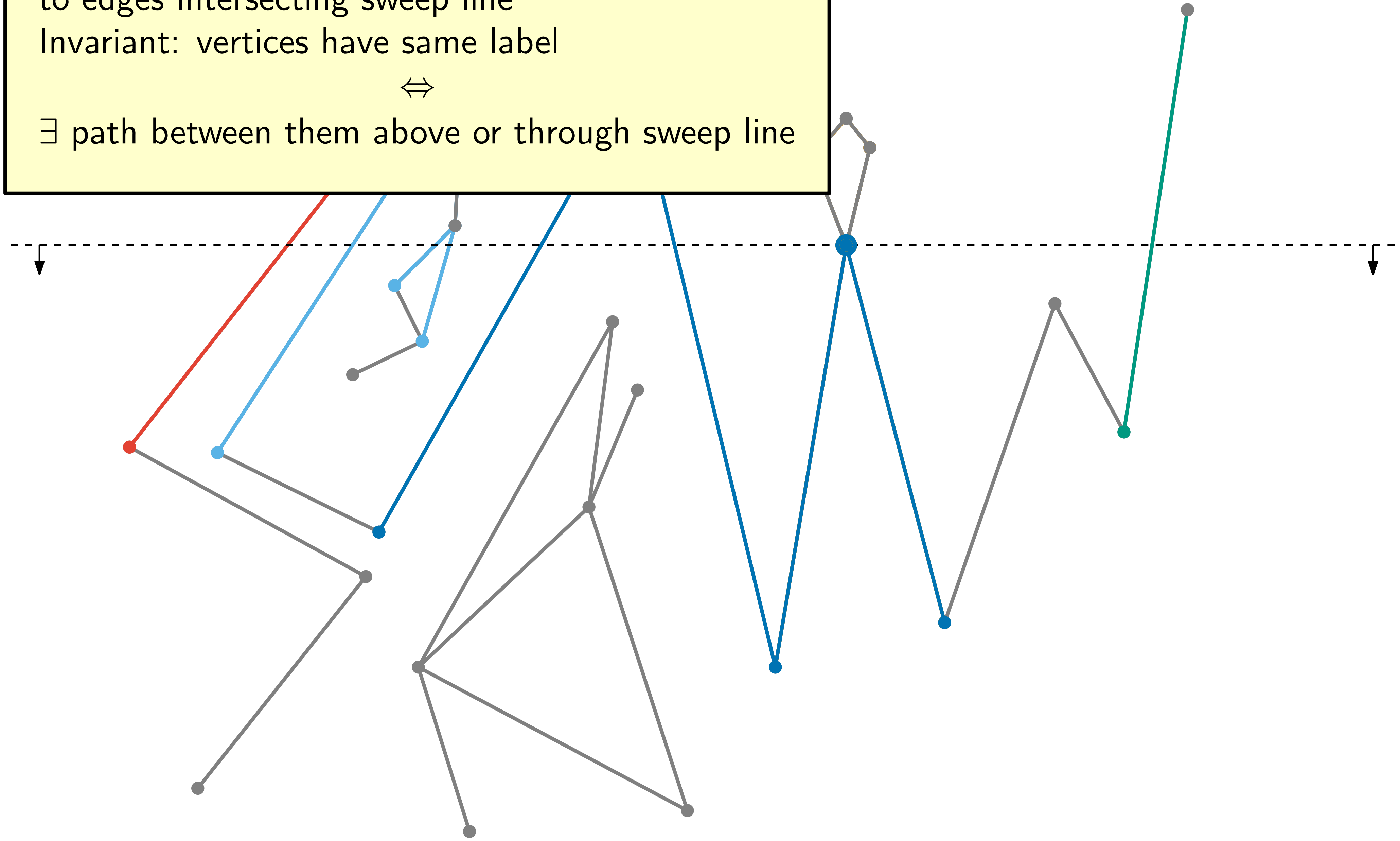

Connected component algorithm
down phase

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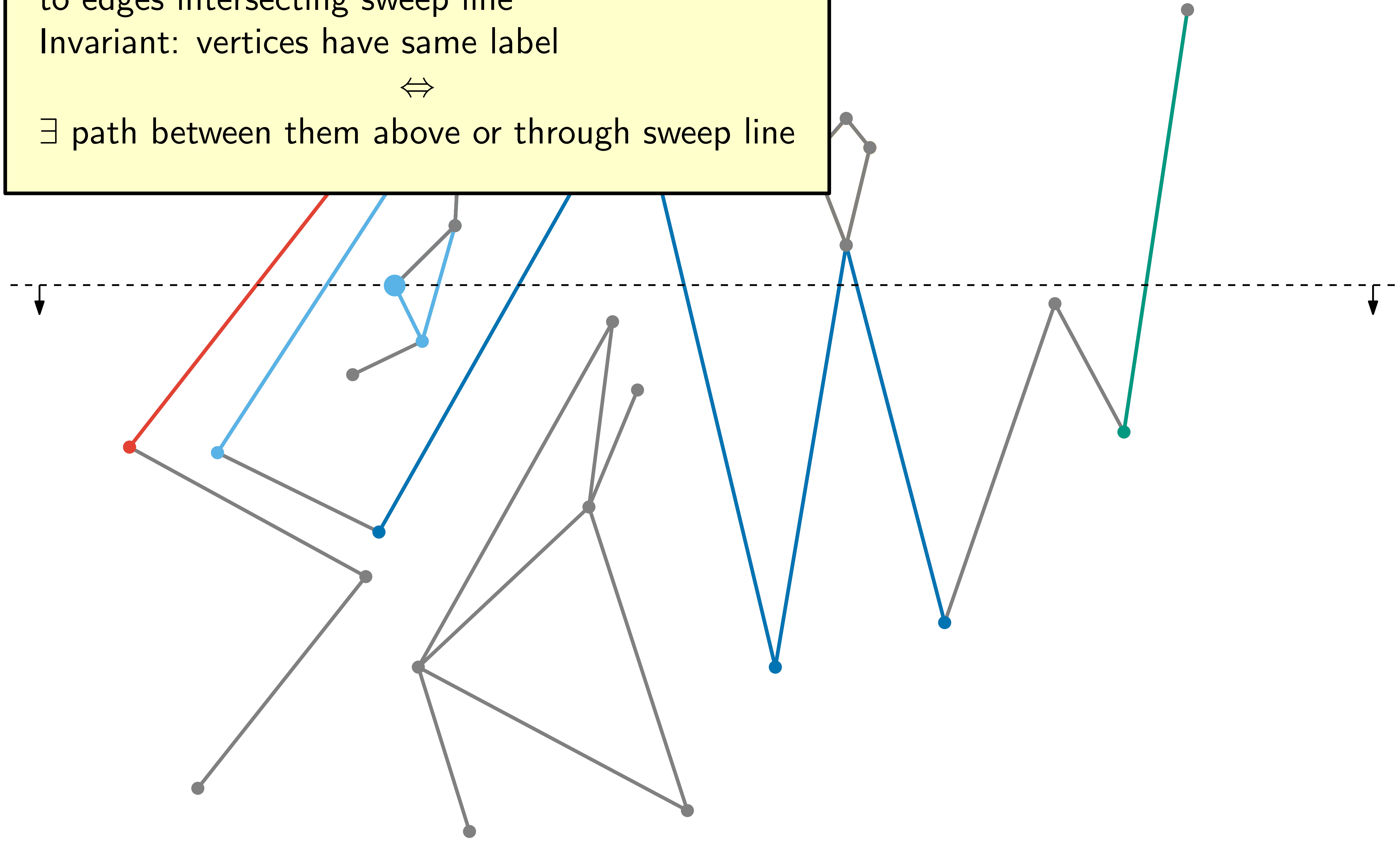

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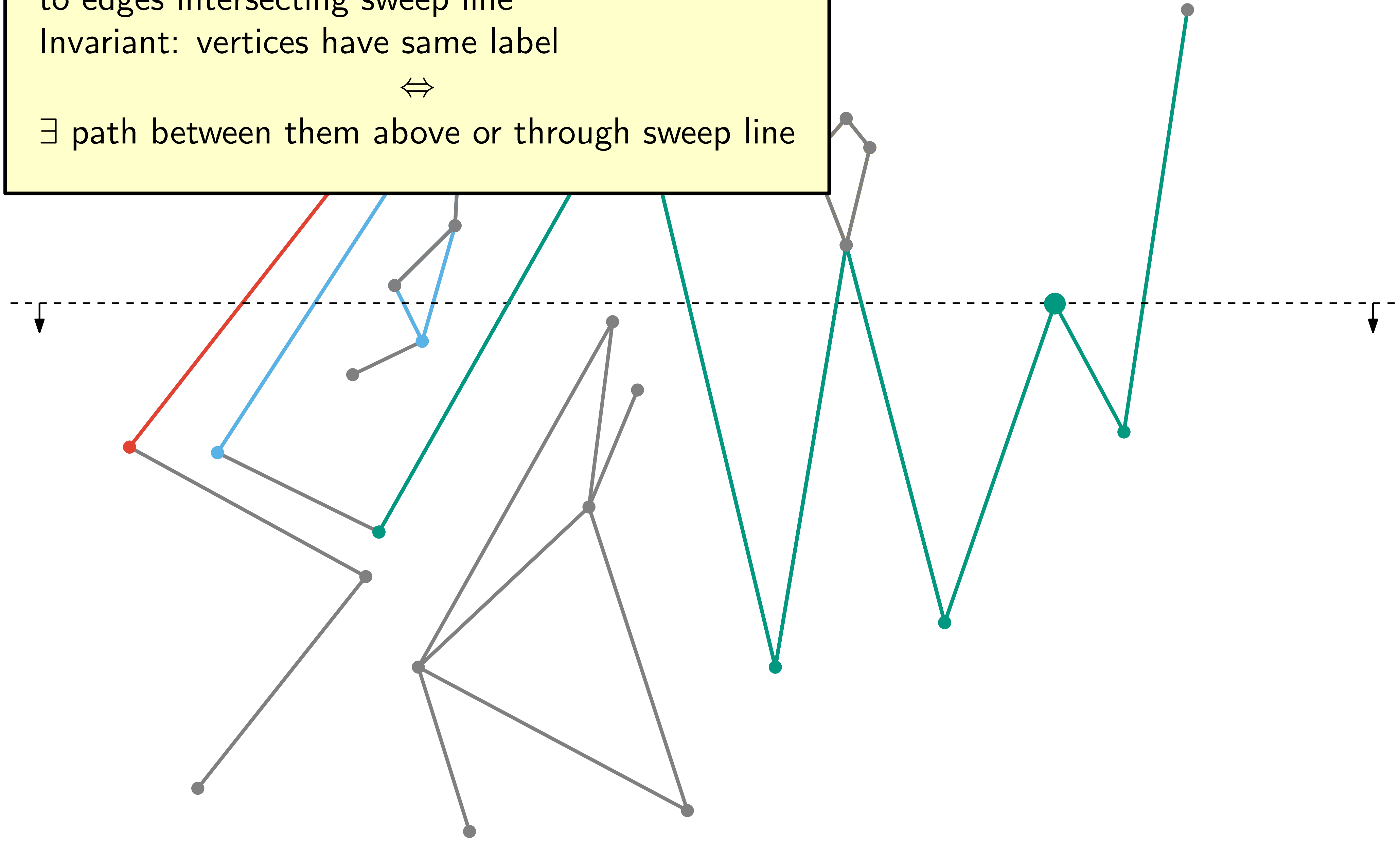

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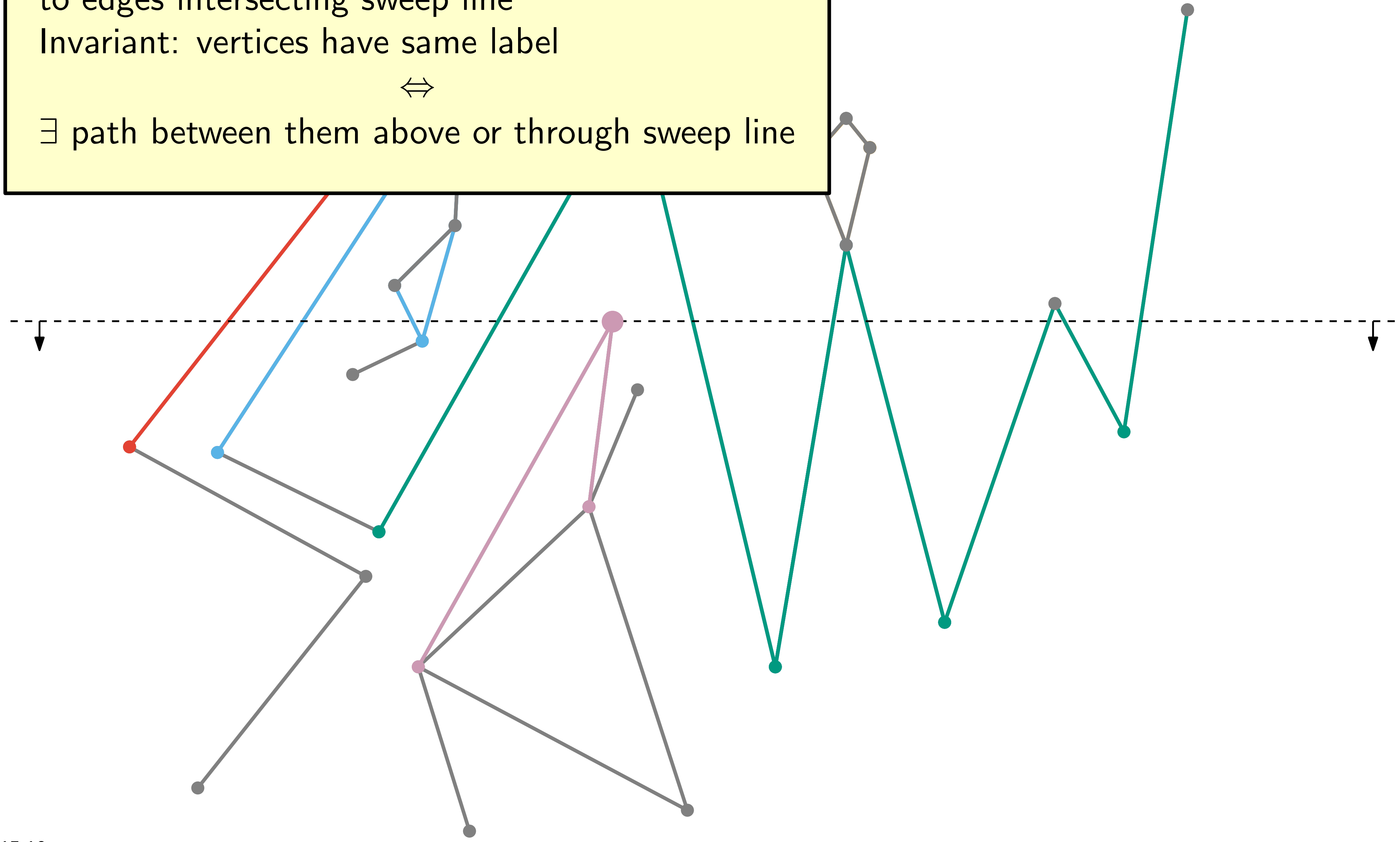

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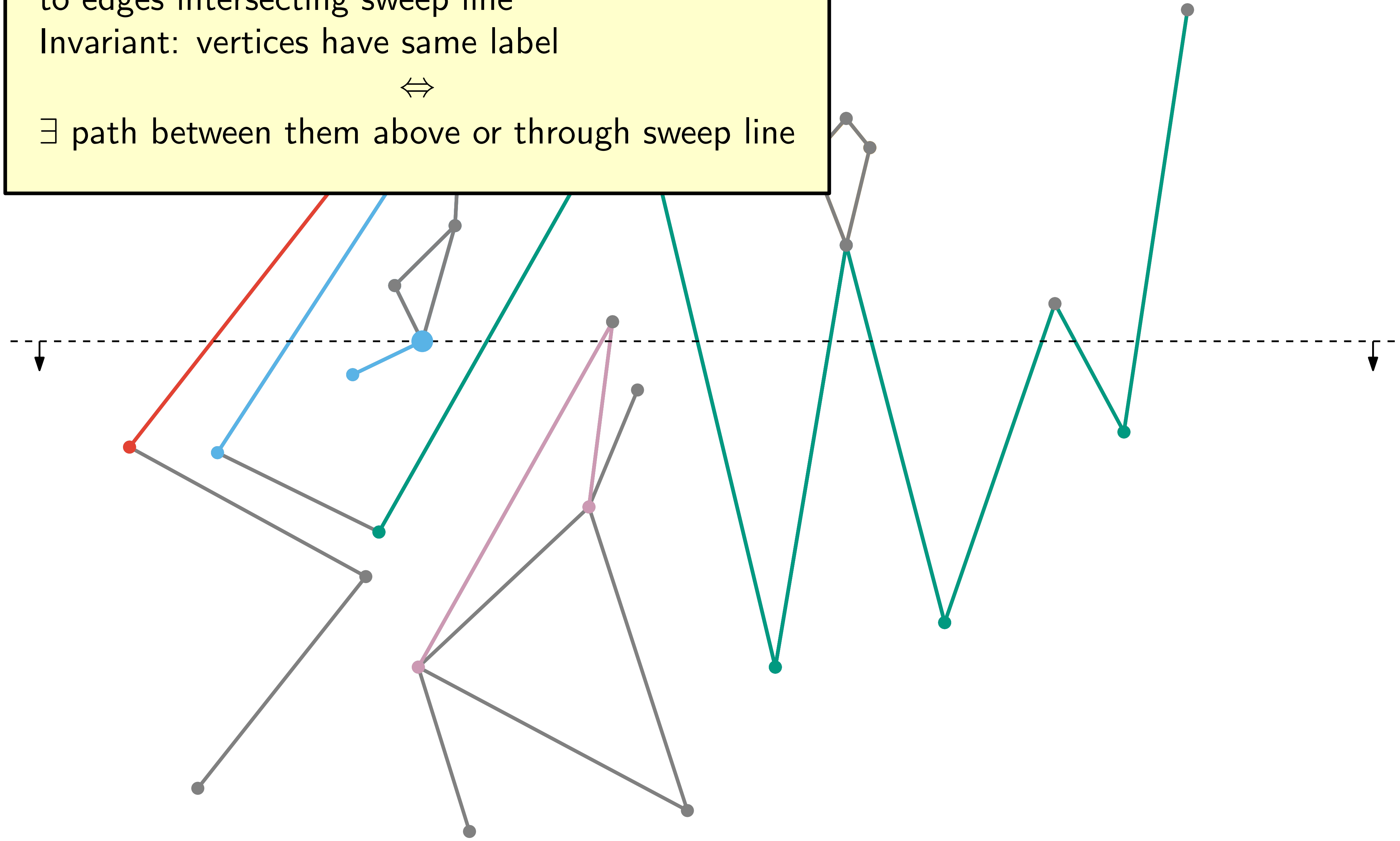

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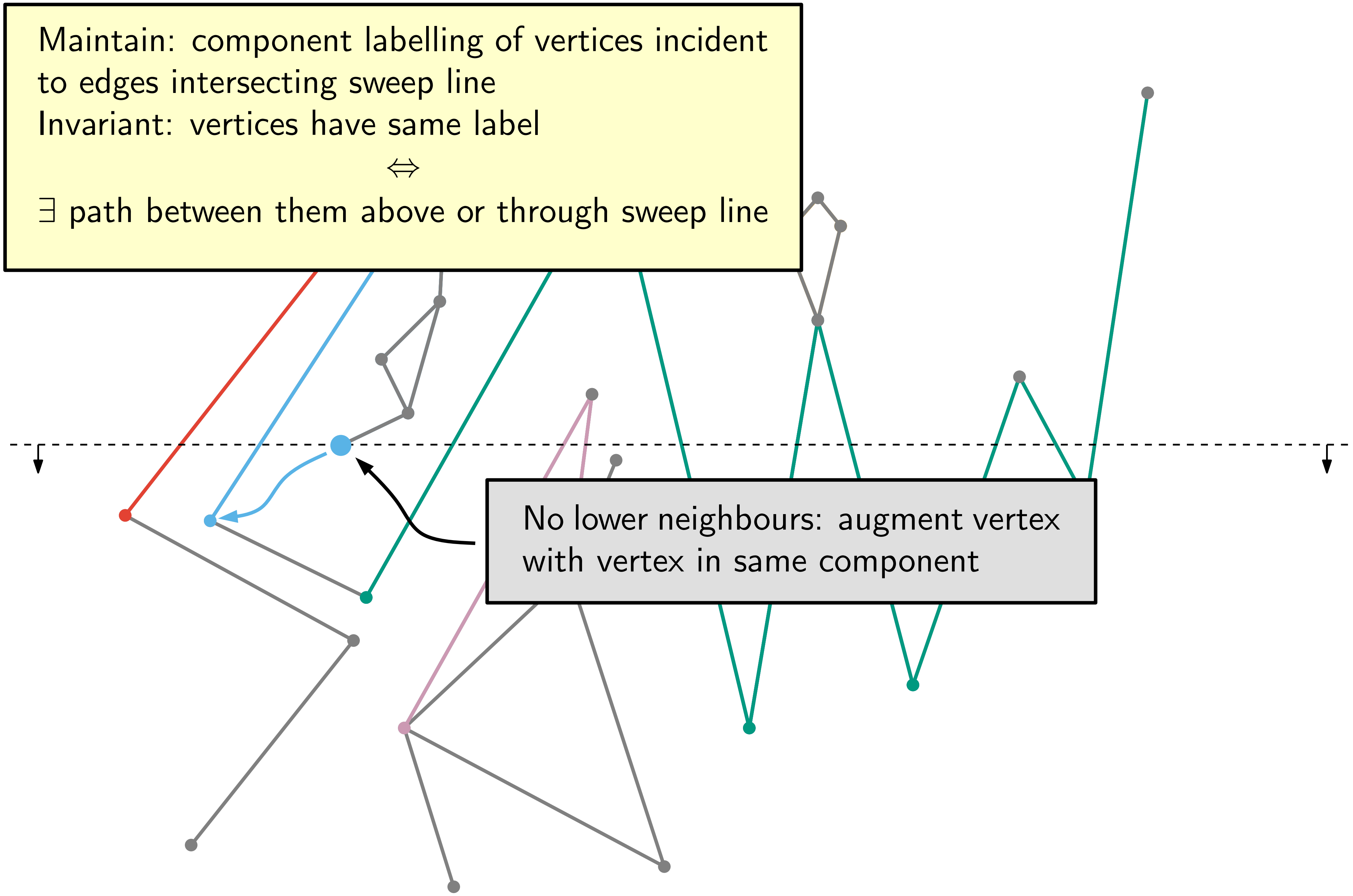

No lower neighbours: augment vertex with vertex in same component

Connected component algorithm

down phase

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Invariant: vertices have same label

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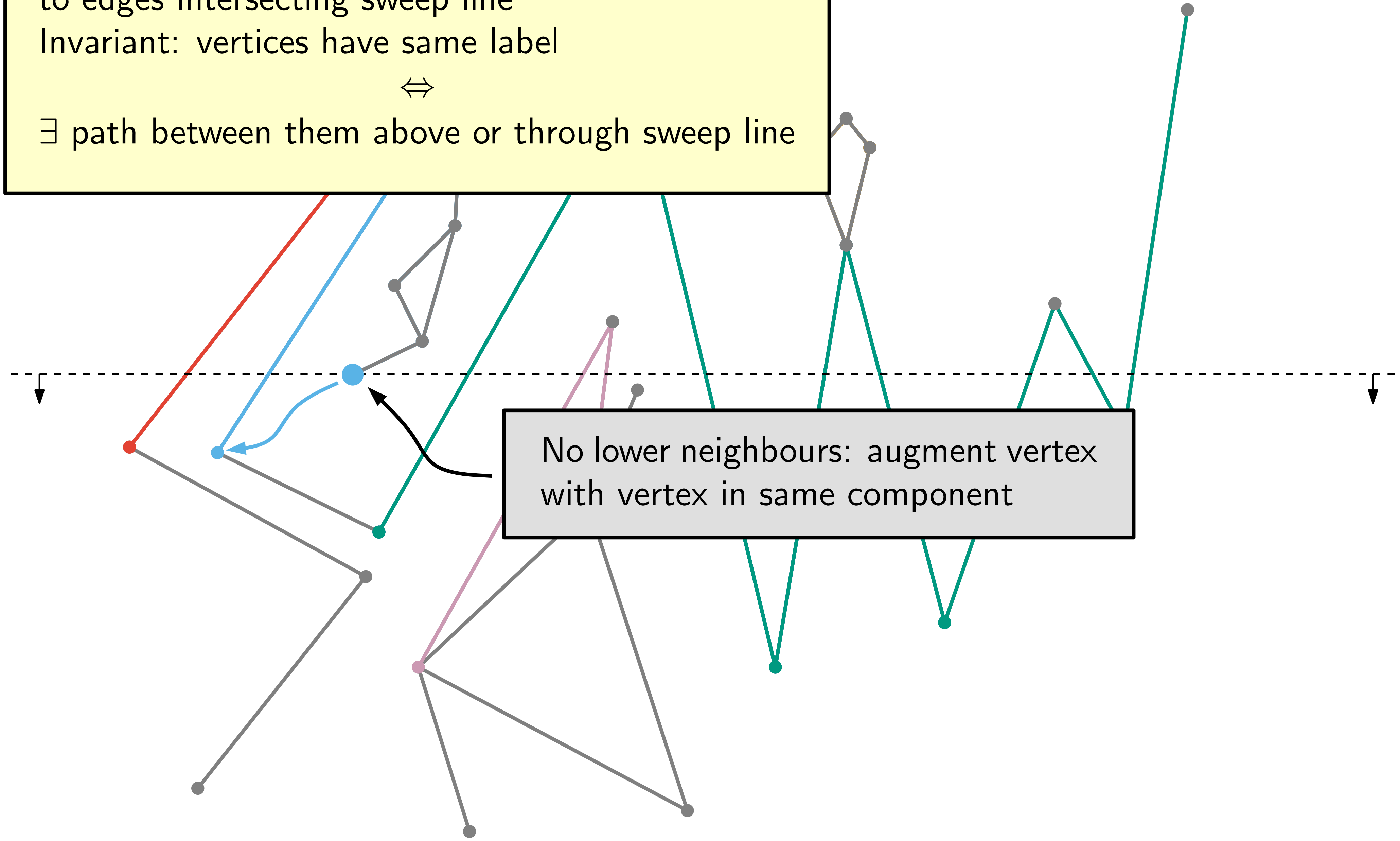

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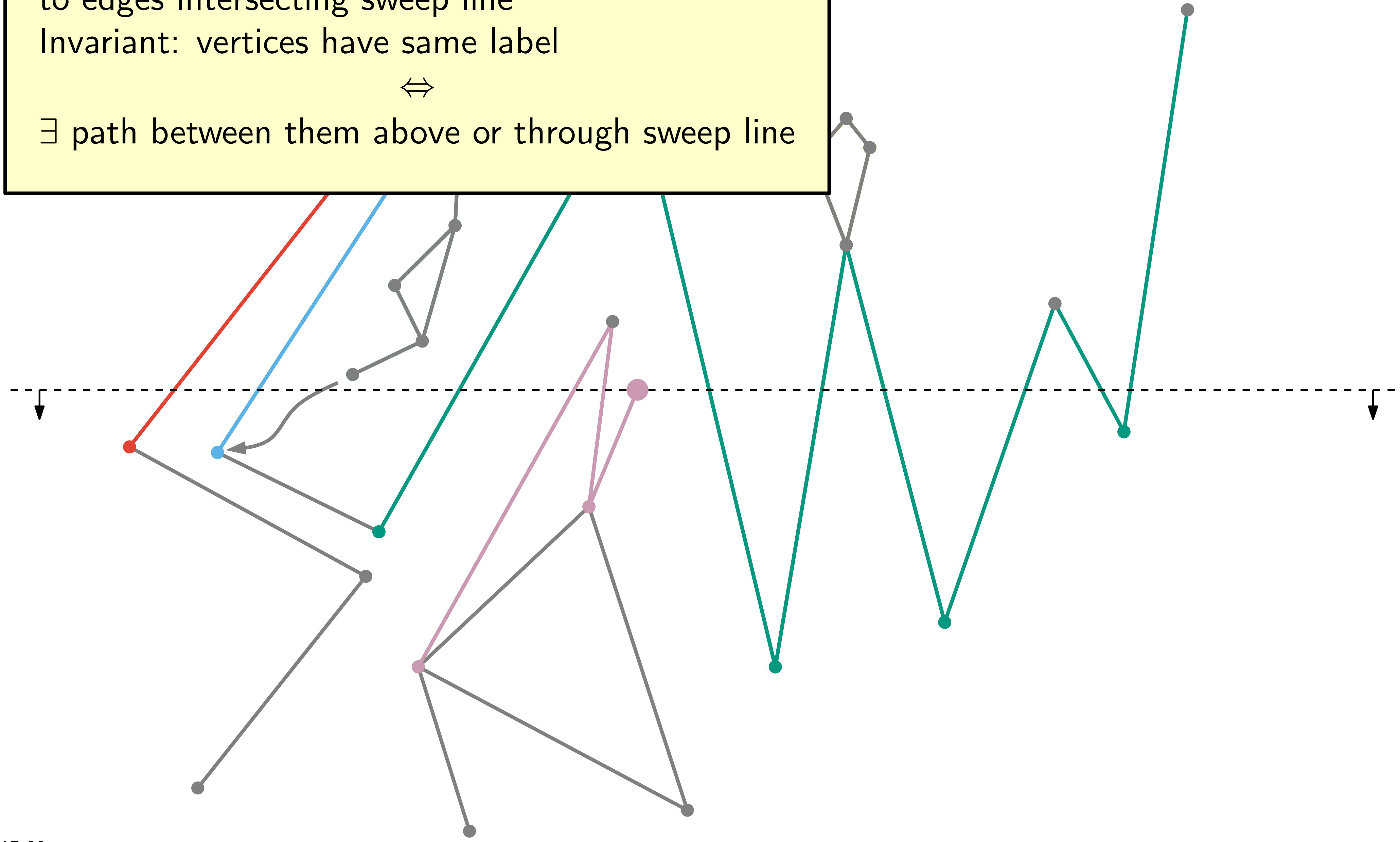

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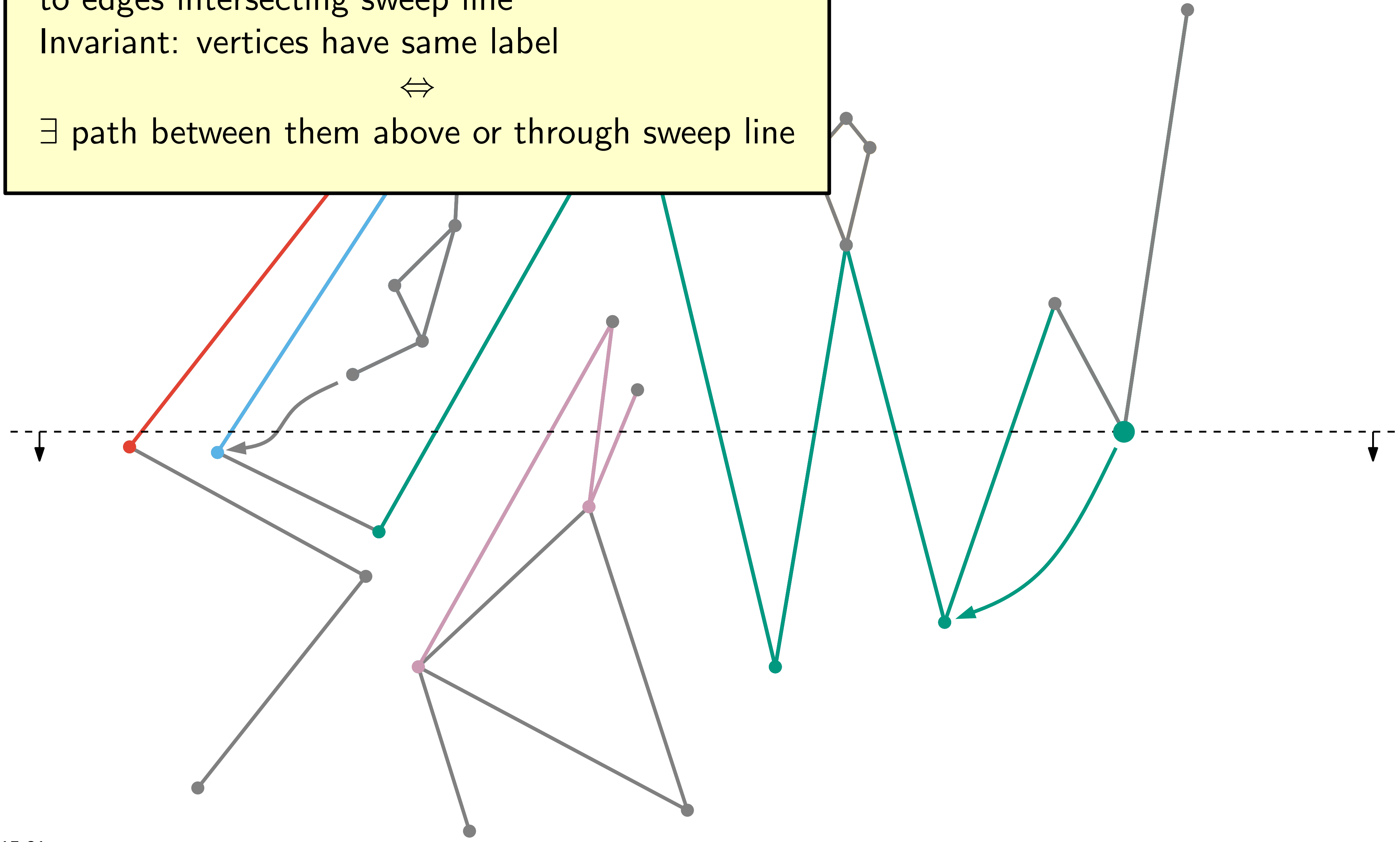

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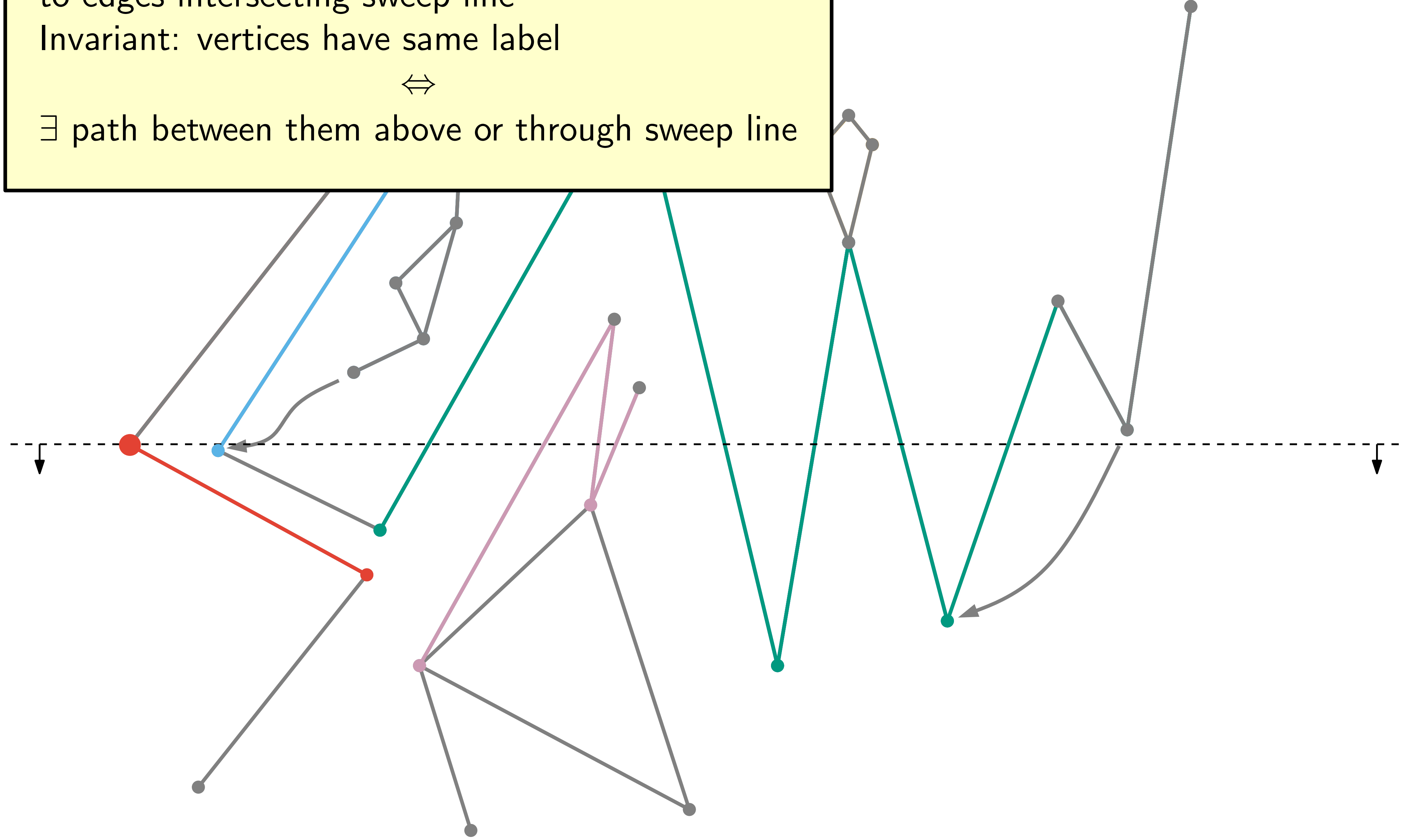

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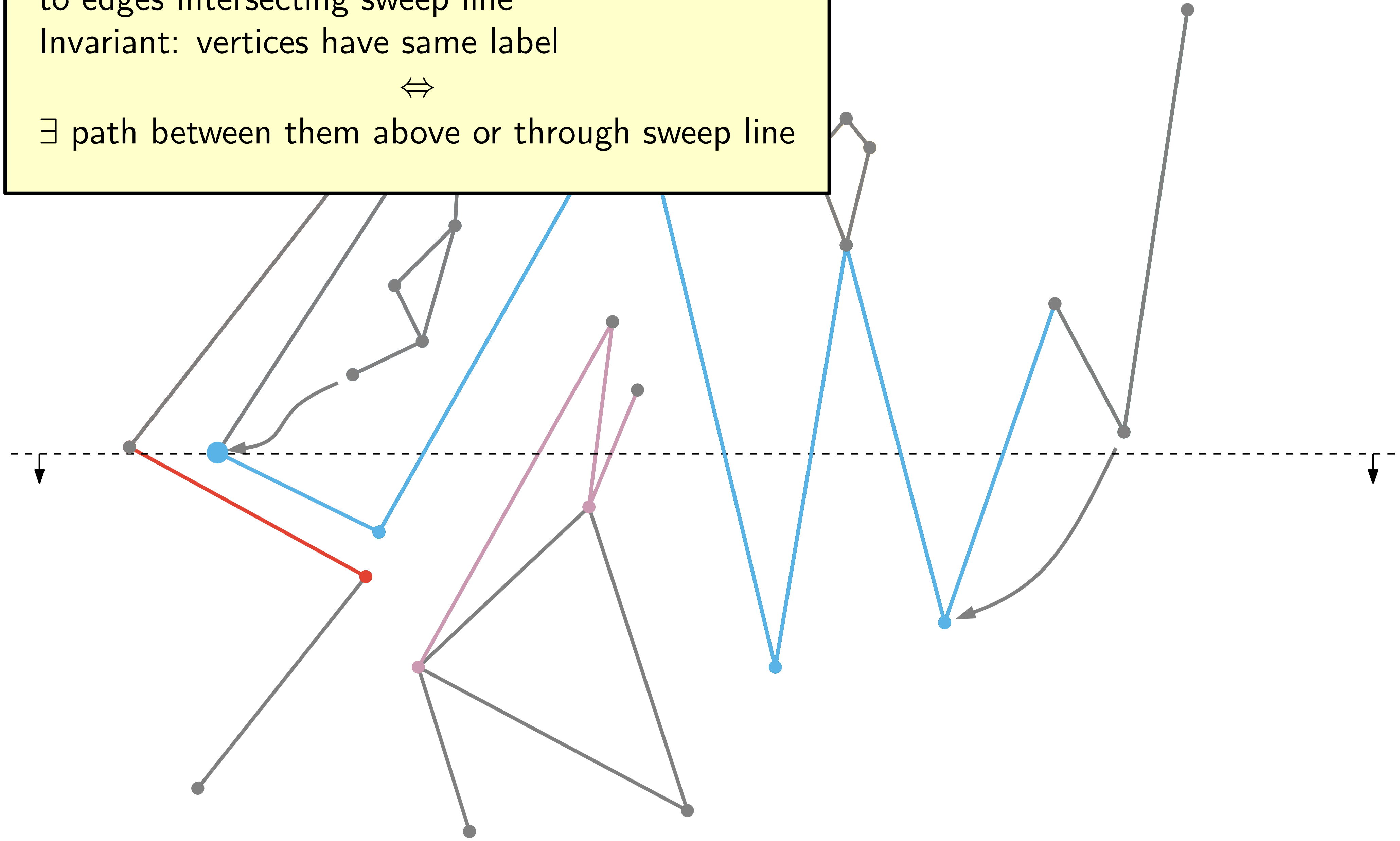

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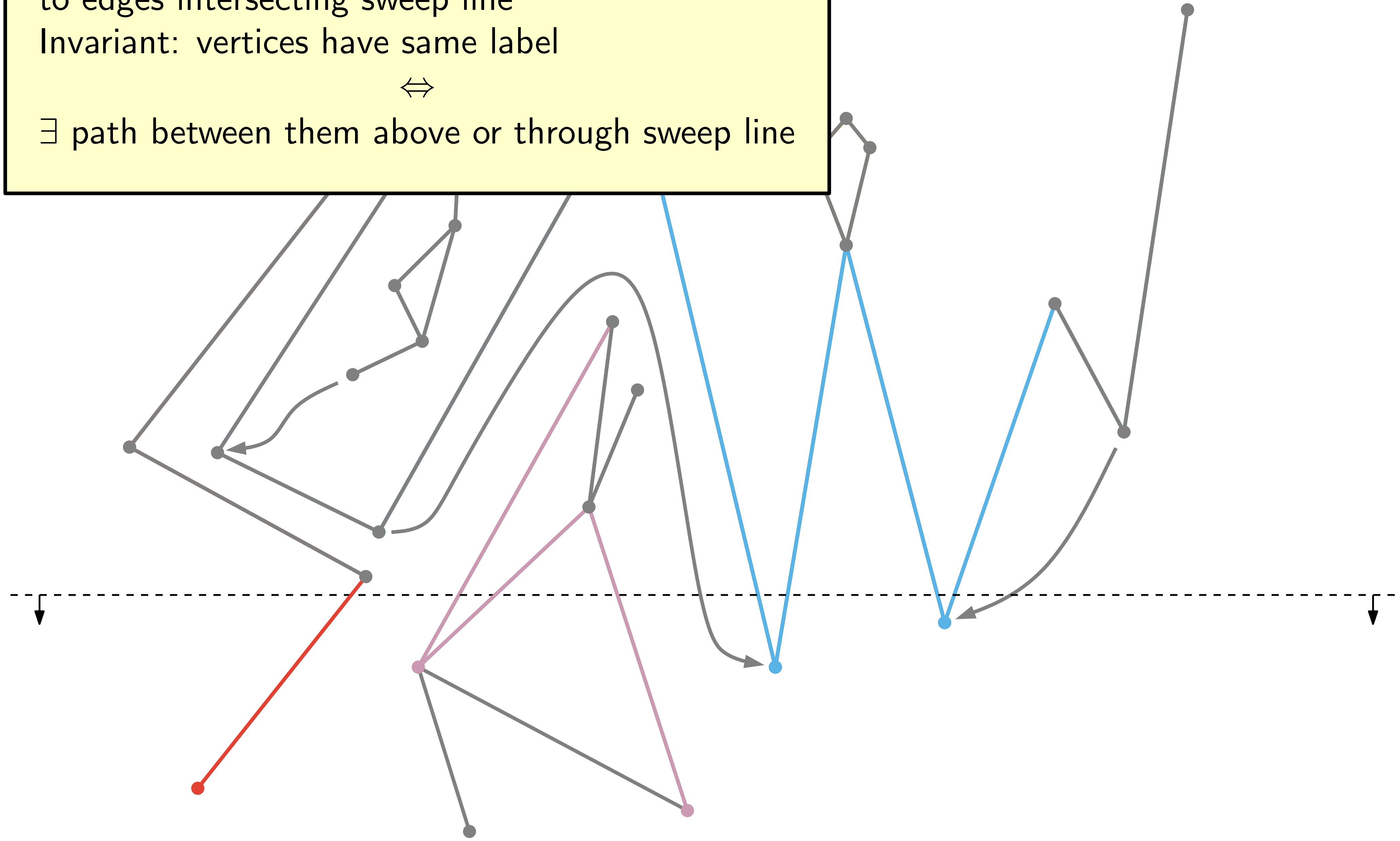

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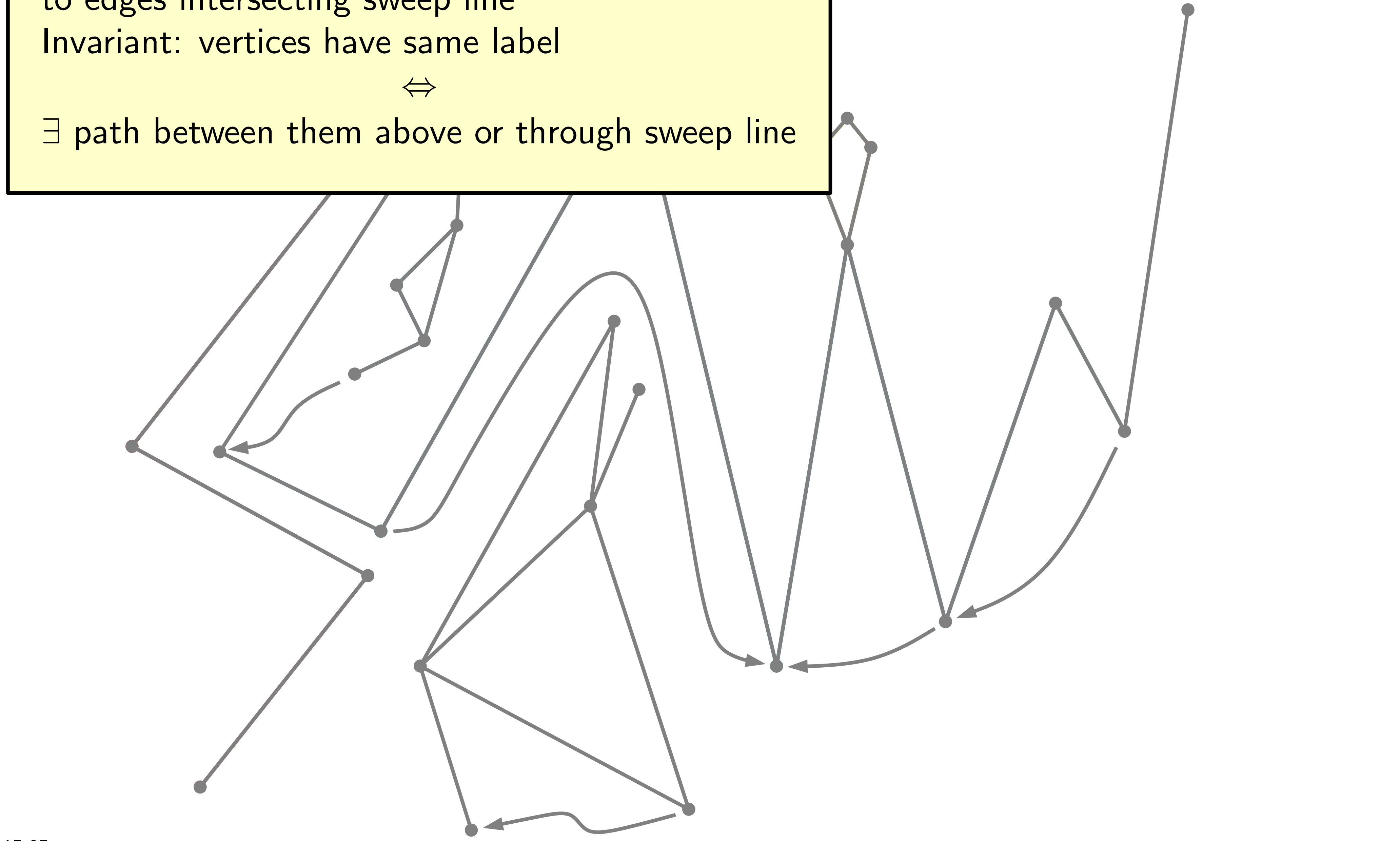
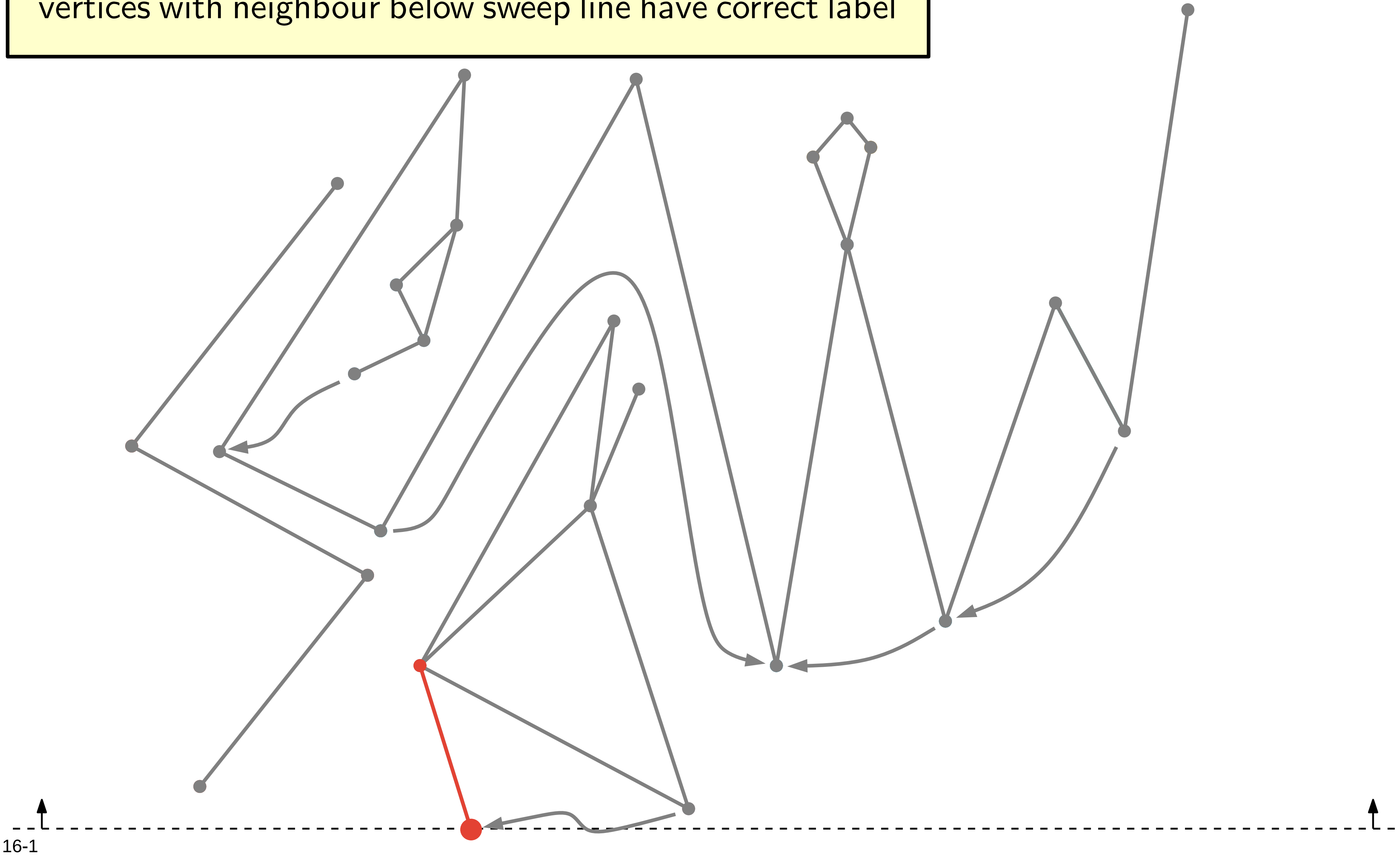


Connected component algorithm

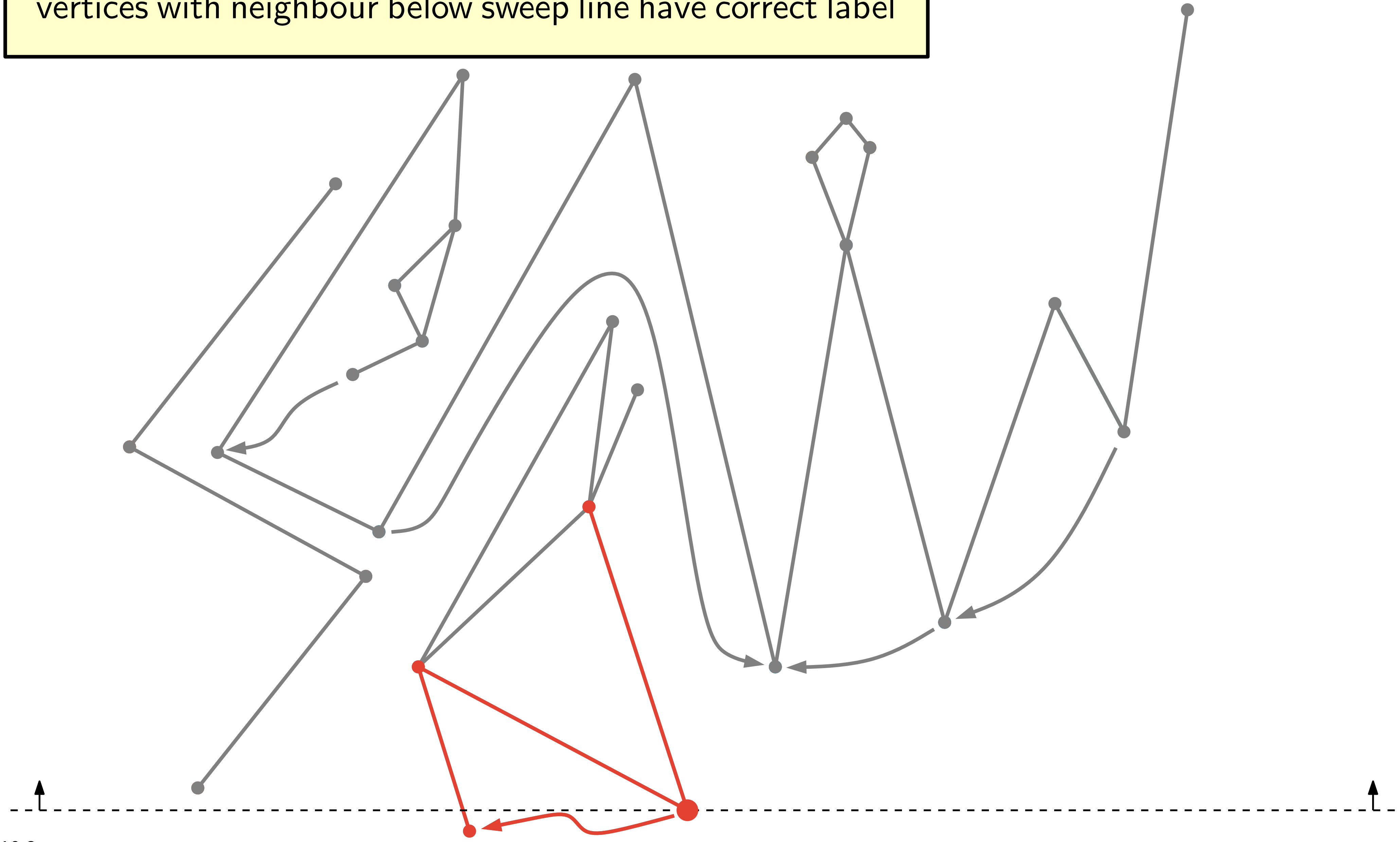
up phase

Invariant:
vertices with neighbour below sweep line have correct label



Connected component algorithm
up phase

Invariant:
vertices with neighbour below sweep line have correct label



Connected component algorithm
up phase

Invariant:
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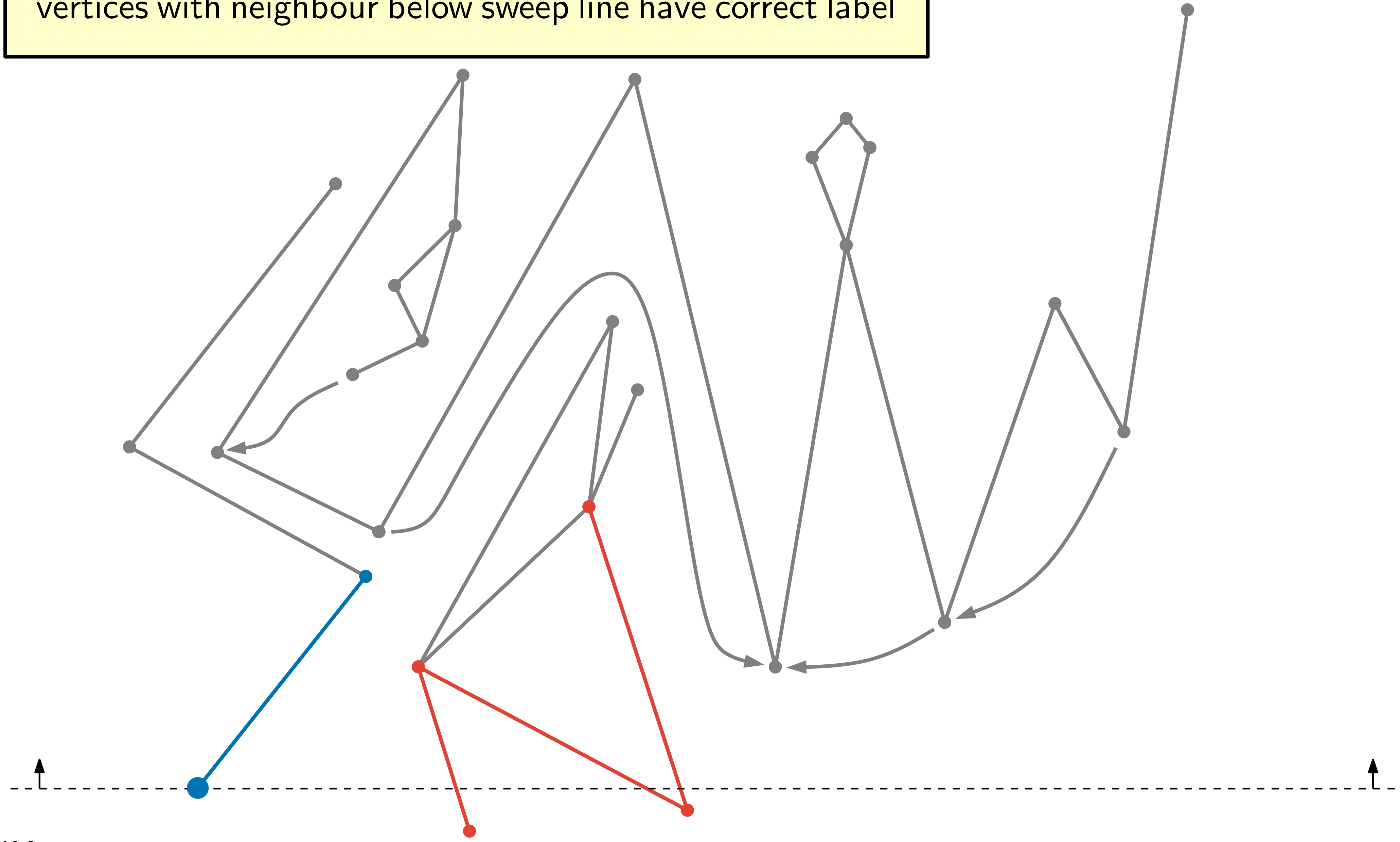

Connected component algorithm

up phase

Invariant:
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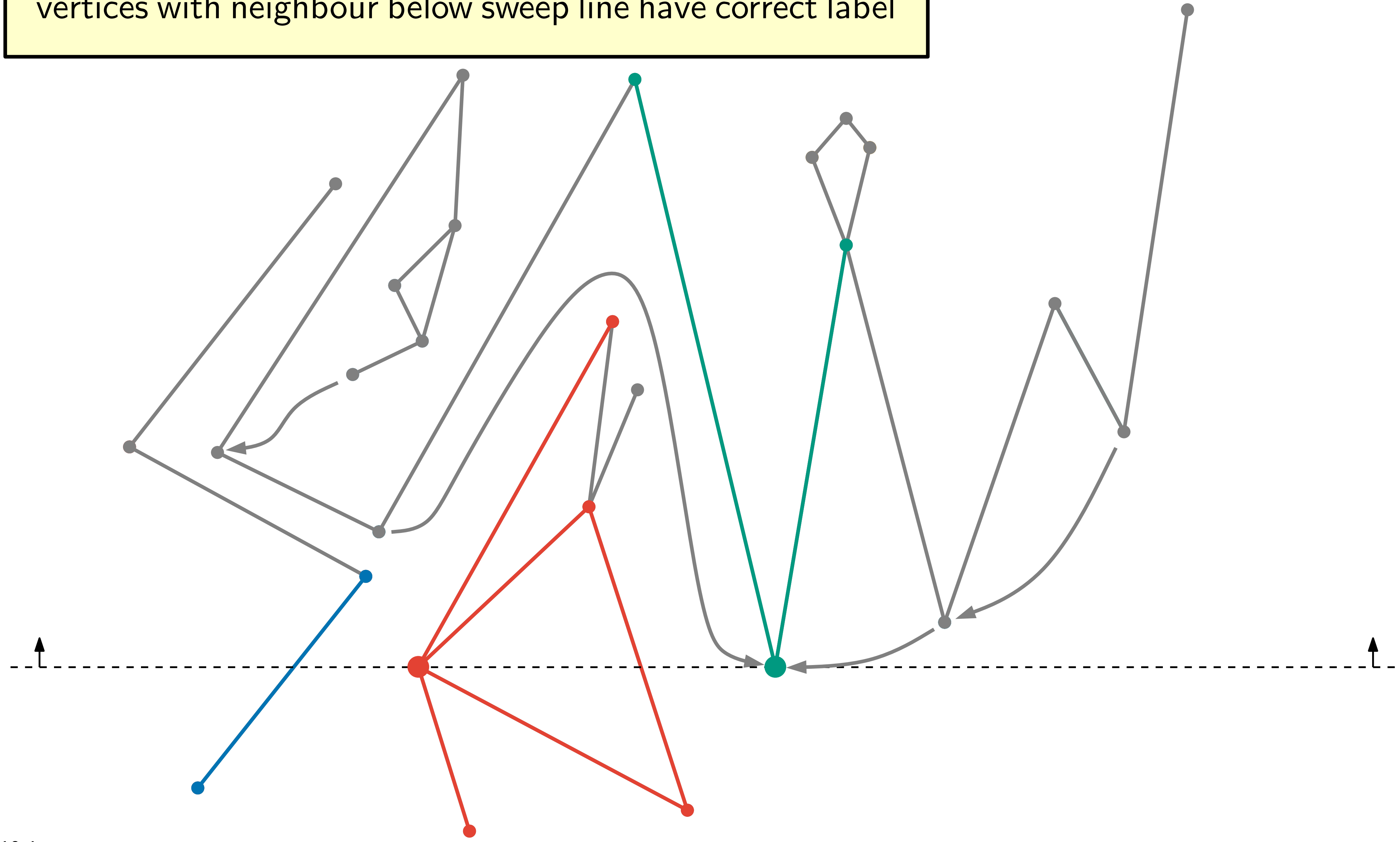

Connected component algorithm
up phase

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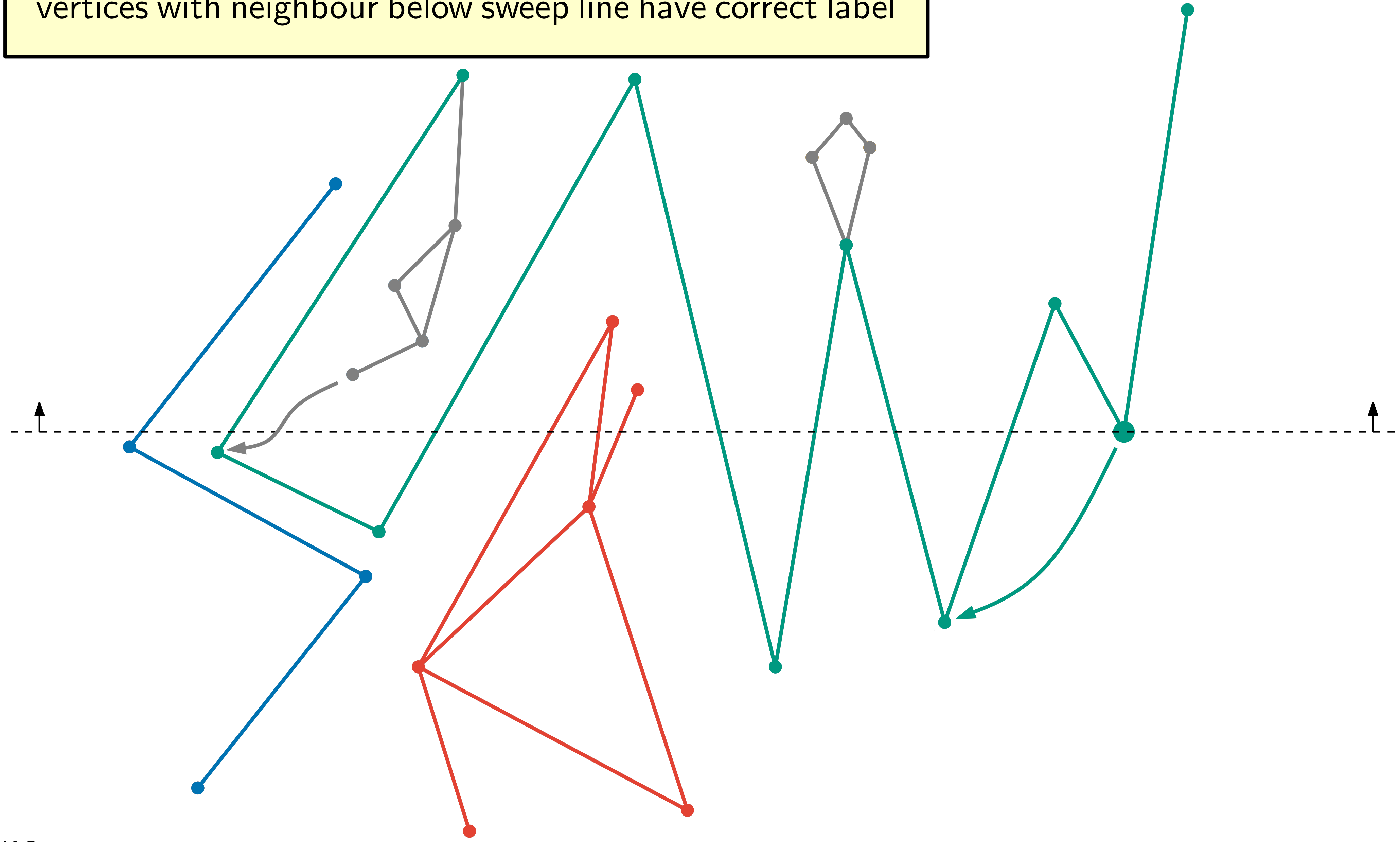

Connected component algorithm

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