Tight printable enclosures and support structures for additive manufacturing

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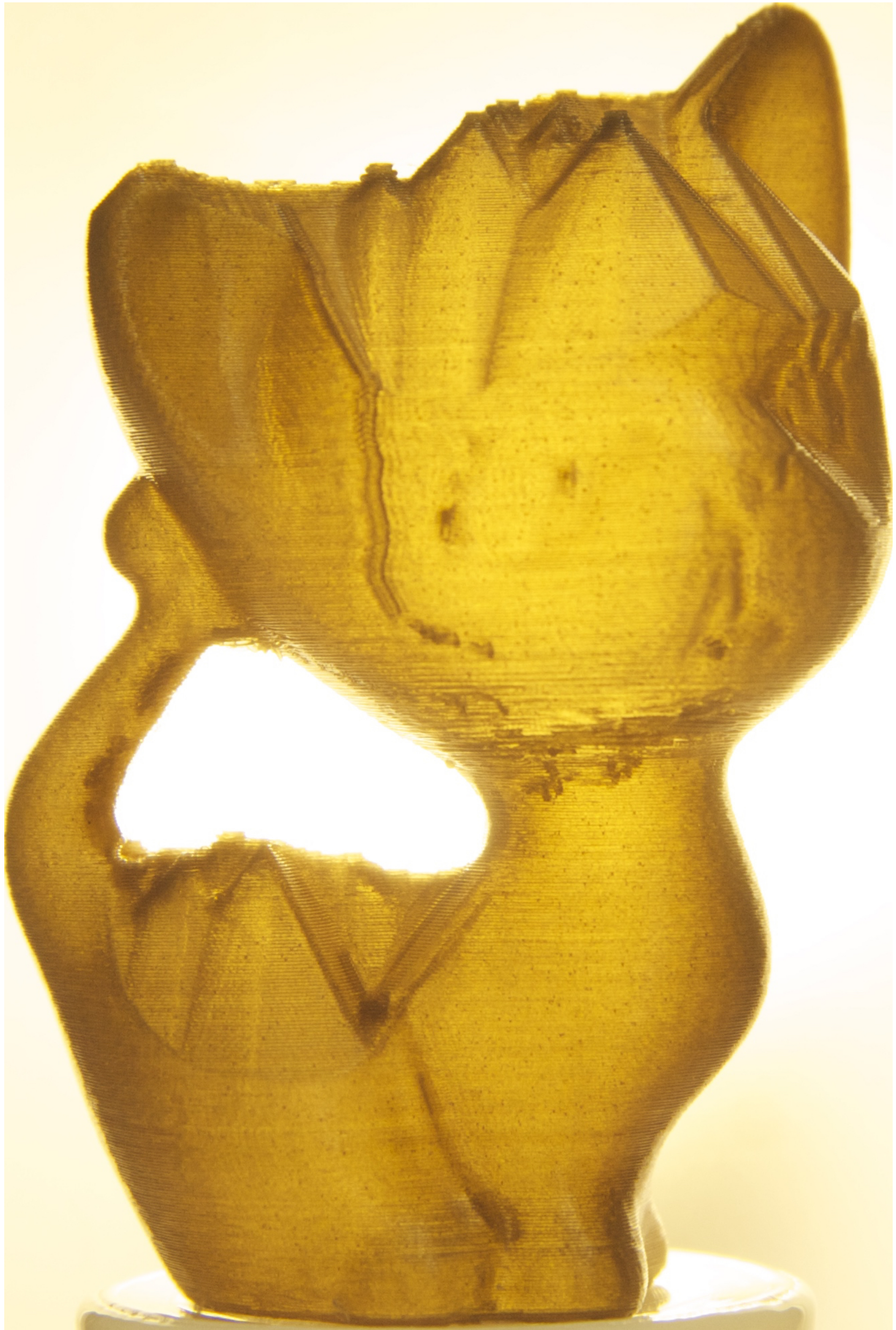
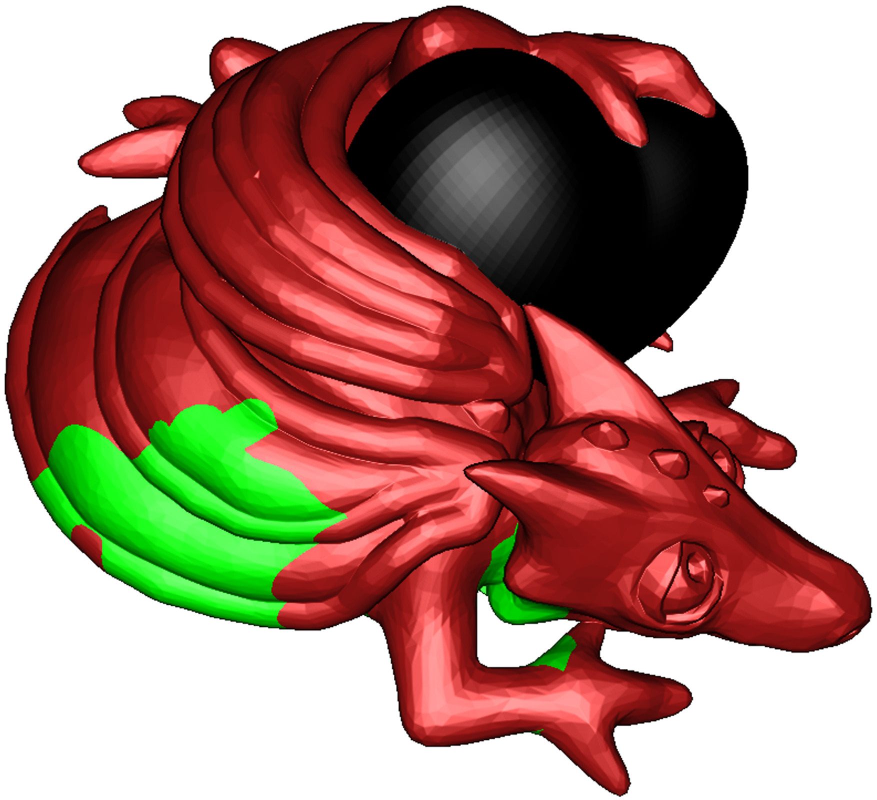
What?

Modeling self-supporting shapes.
Easiest form of printabilty.



Motivations come from dual-material printing



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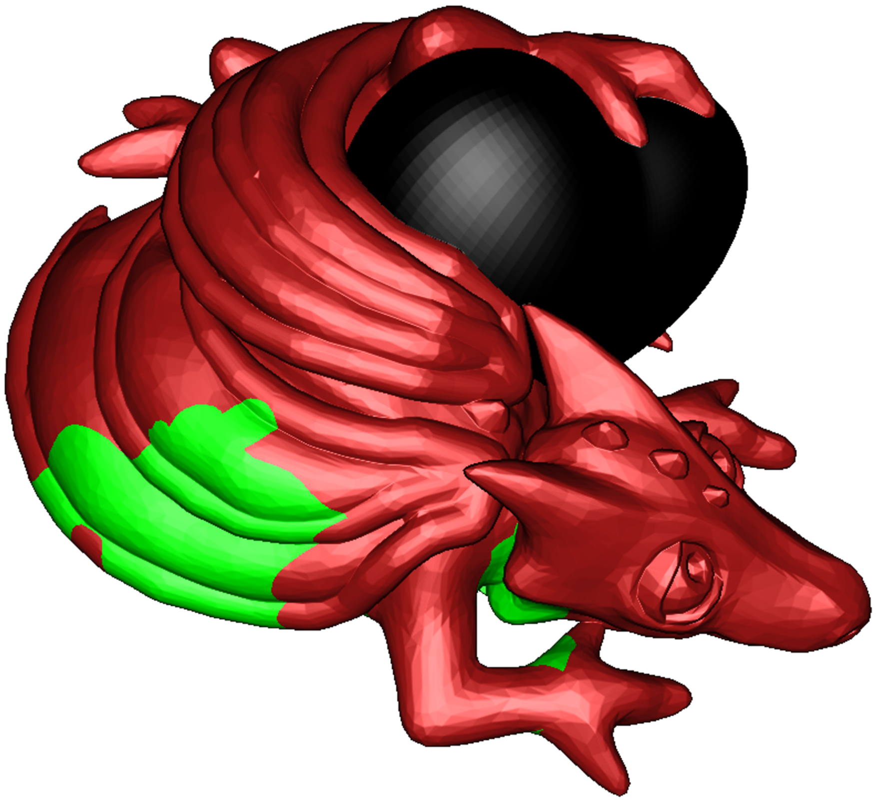

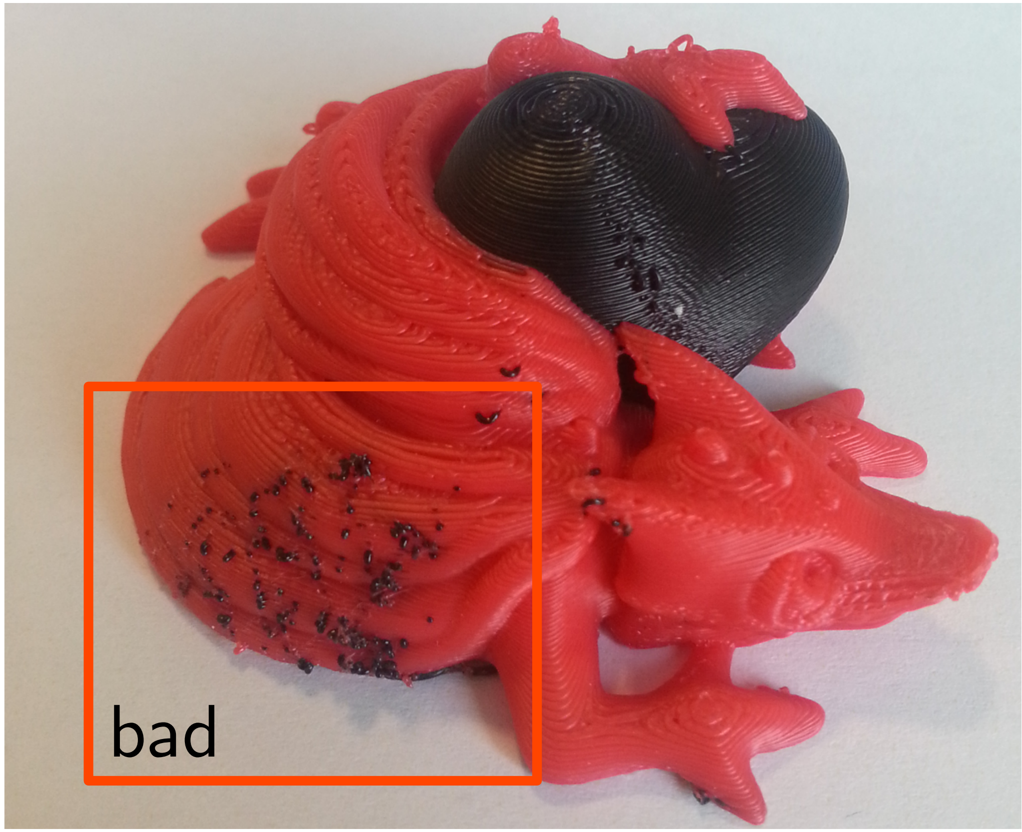

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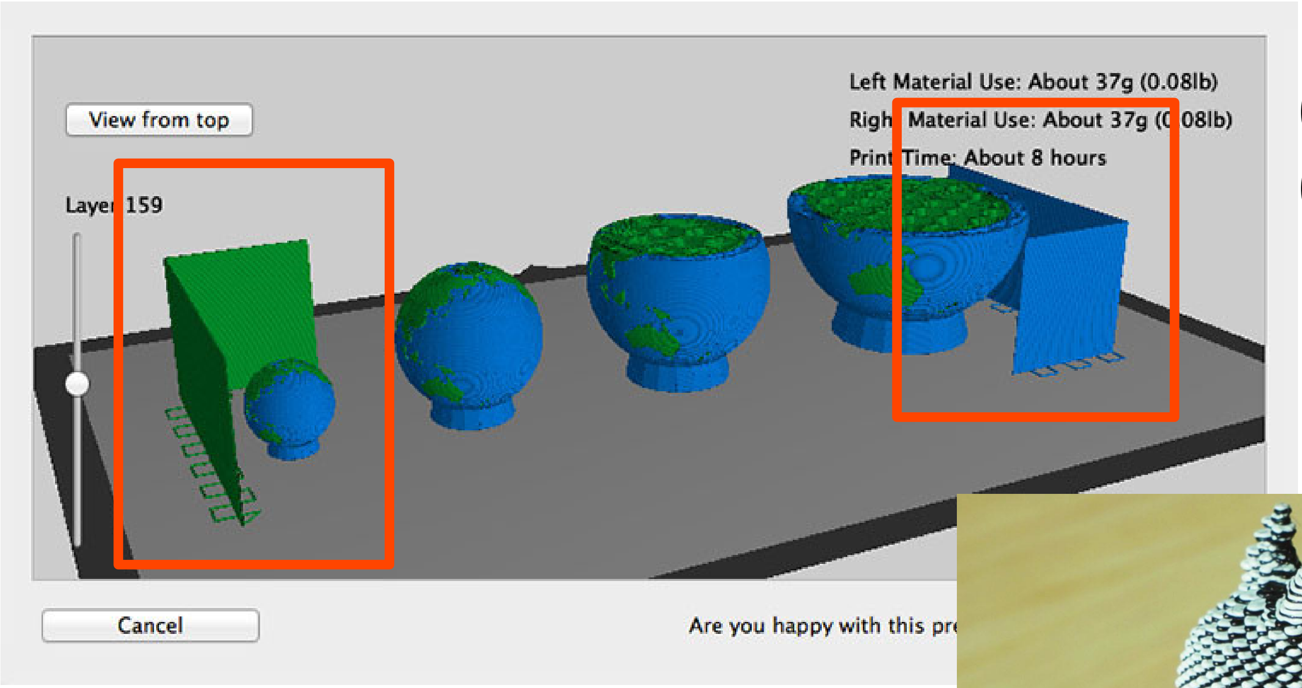
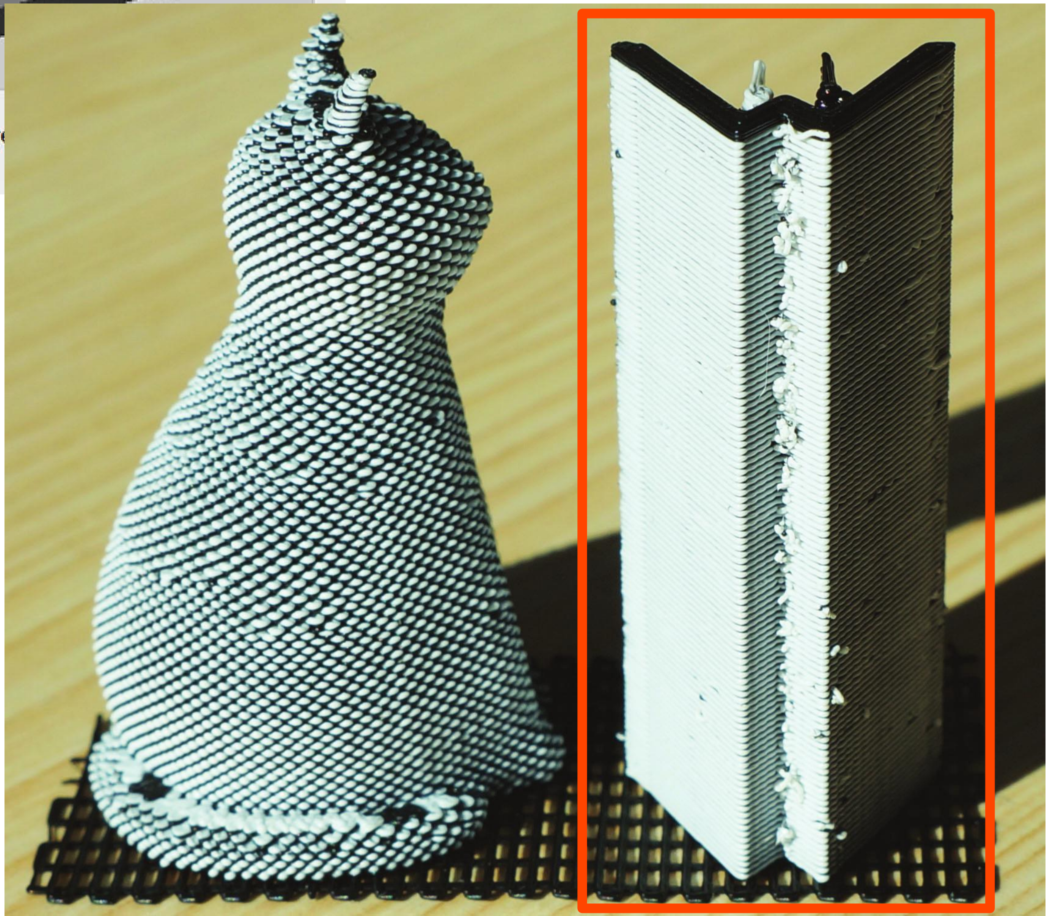


Makerware (http://www.plot-it.co.uk) (Also, ReprapHost, KissSlicer, ...)

Reiner *et al.*[Eurographics'14]



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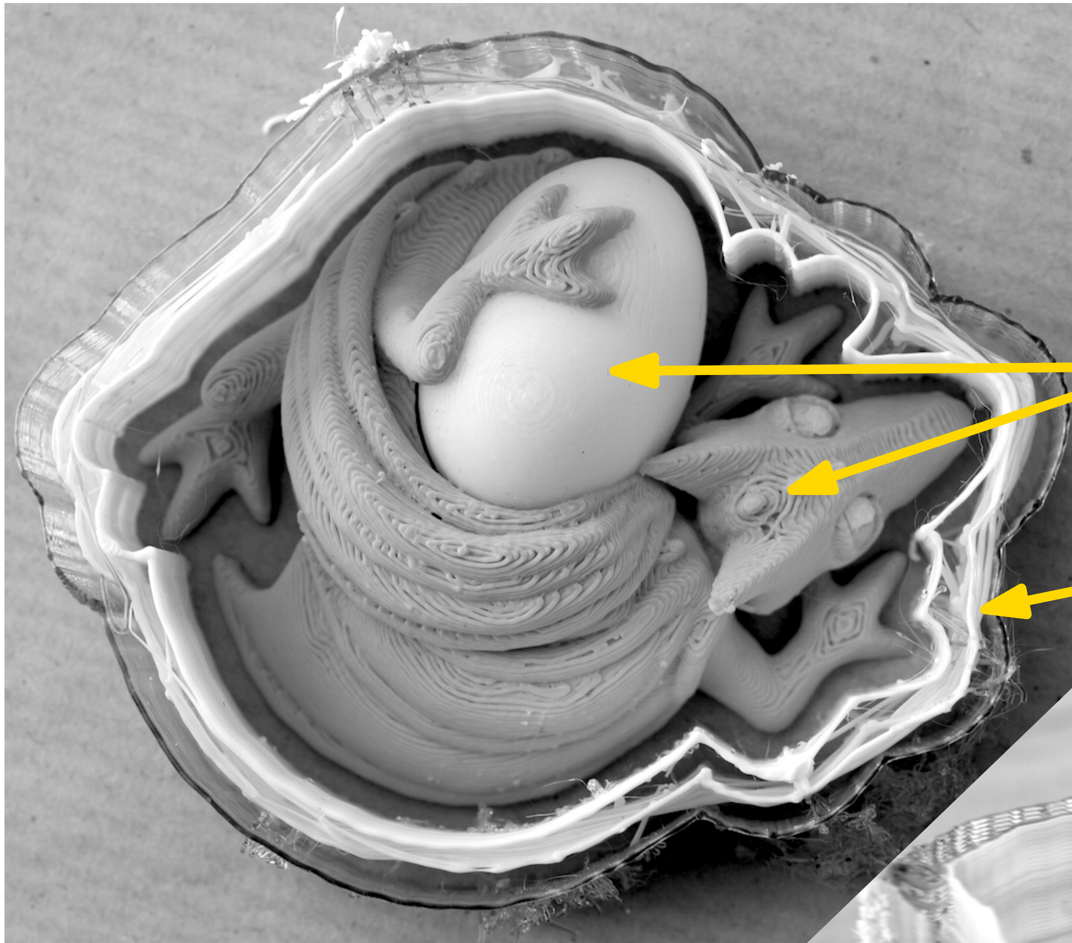
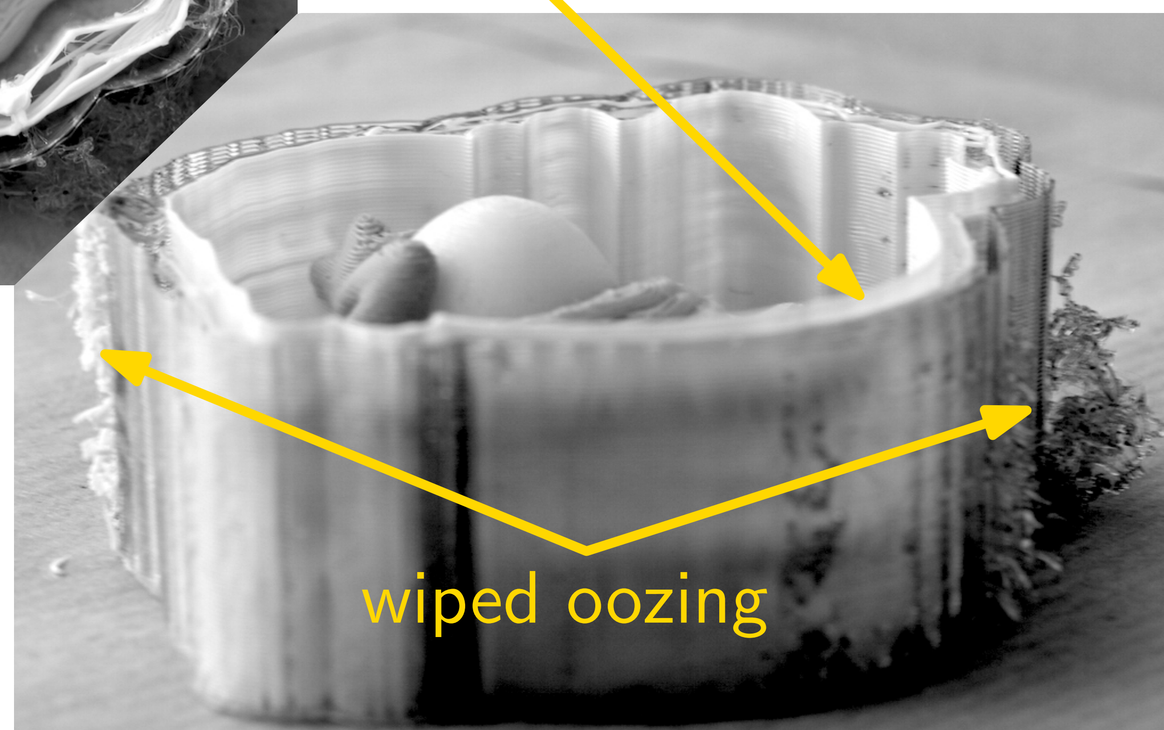


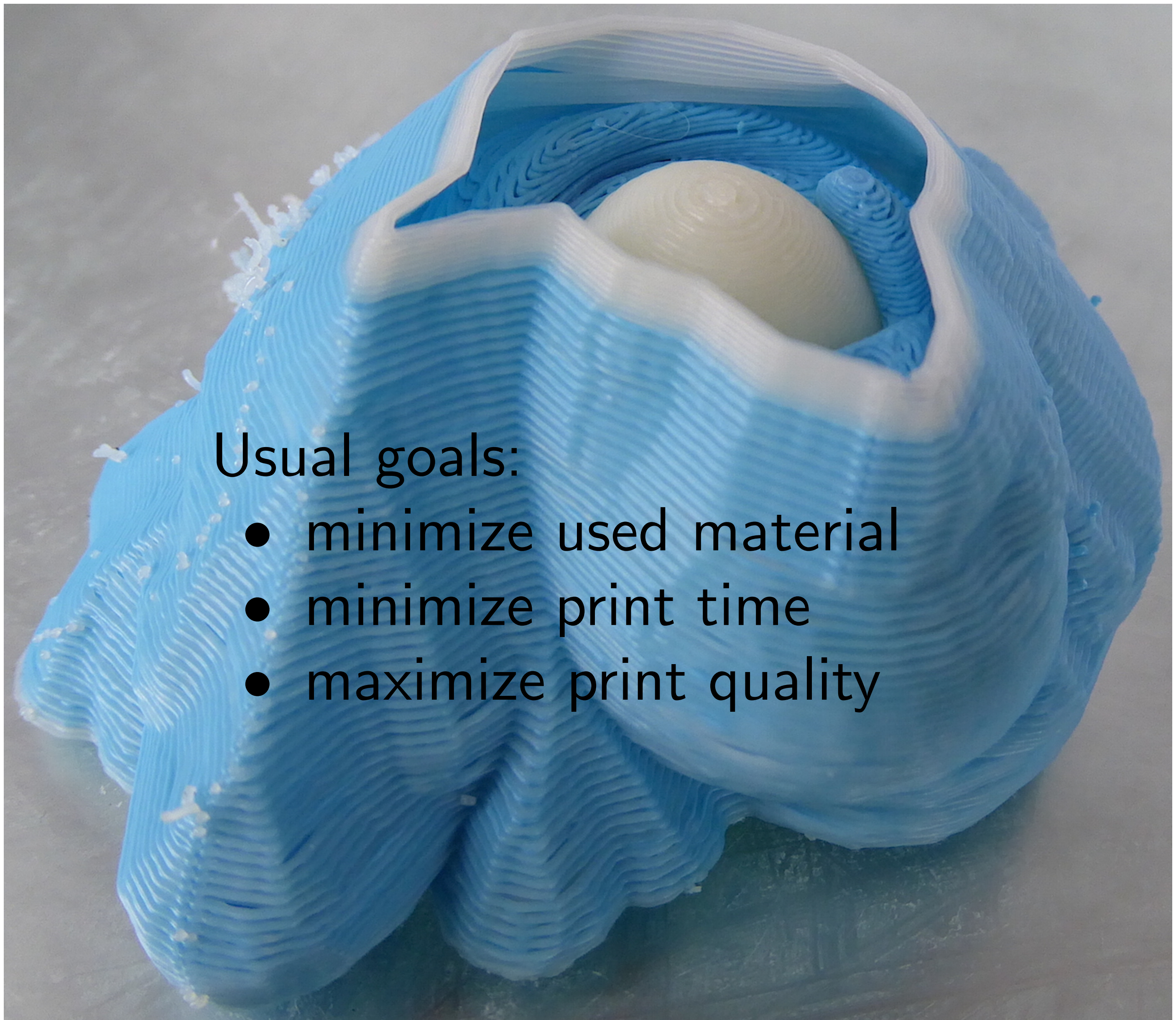
Hergel and Lefebvre [Eurographics'14]

side view:



Motivations come from dual-material printing

Can we model a "protective enclosure" that is even more tightly fit around the object?



Usual goals:

- minimize used material
- minimize print time
- maximize print quality

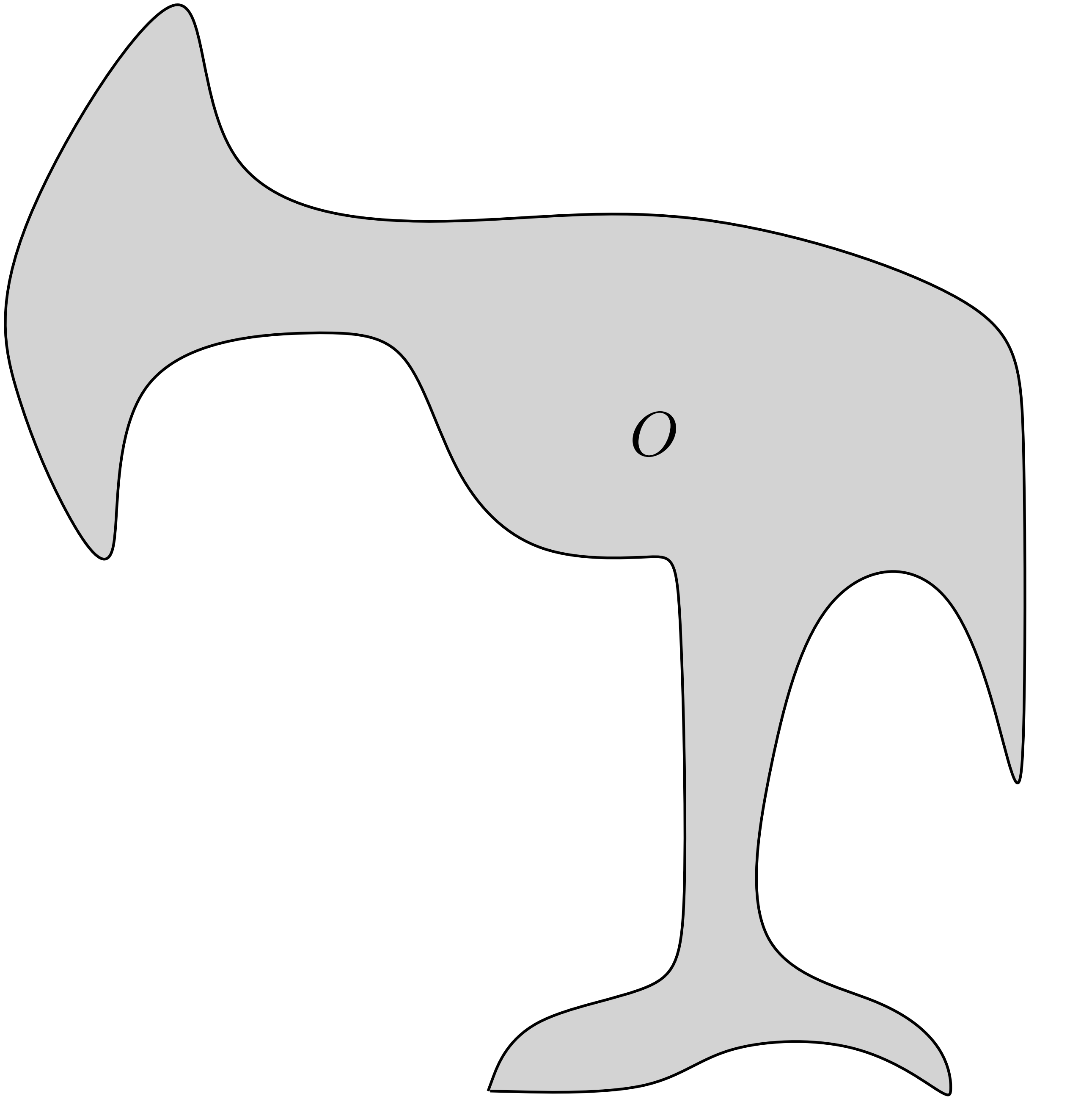
Contributions

- Analysis of the enclosure modeling problem

- Definition of the simple-enclosure and the two-pass technique to compute it

- Applications to
  - Dual-color printing (same as “ooze shield” in Cura)
  - Modeling large cavities (most interesting)
  - Modeling support structures

The problem



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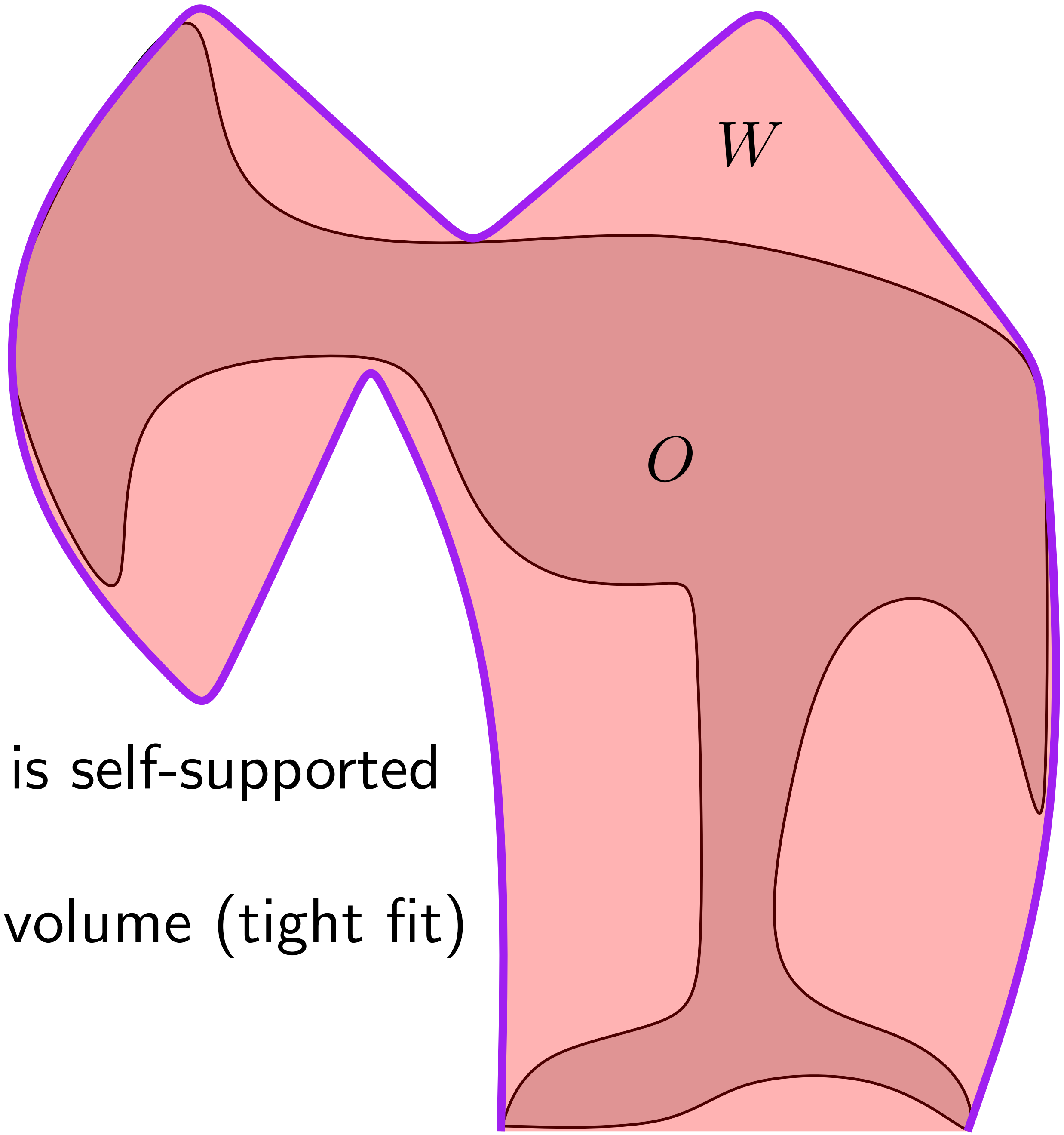
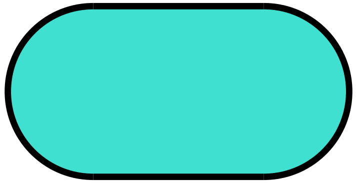


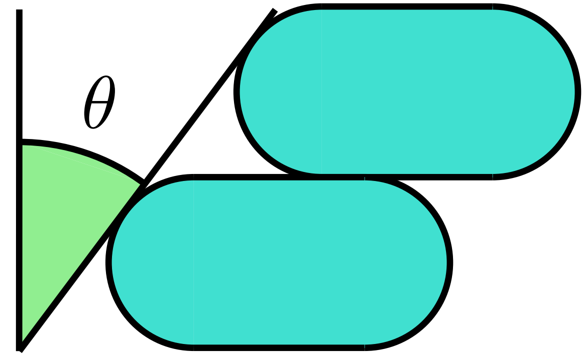
- Boundary of W is self-supported
- $W \supset O$
- W has minimal volume (tight fit)

The problem

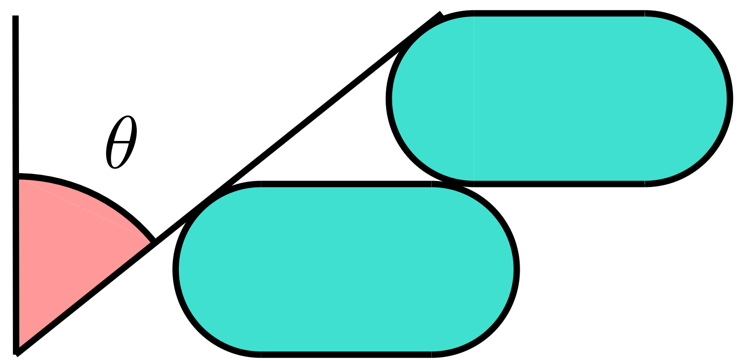


filament cross section (e.g., 0.4mm wide, 0.2mm high)

OK



angle too large



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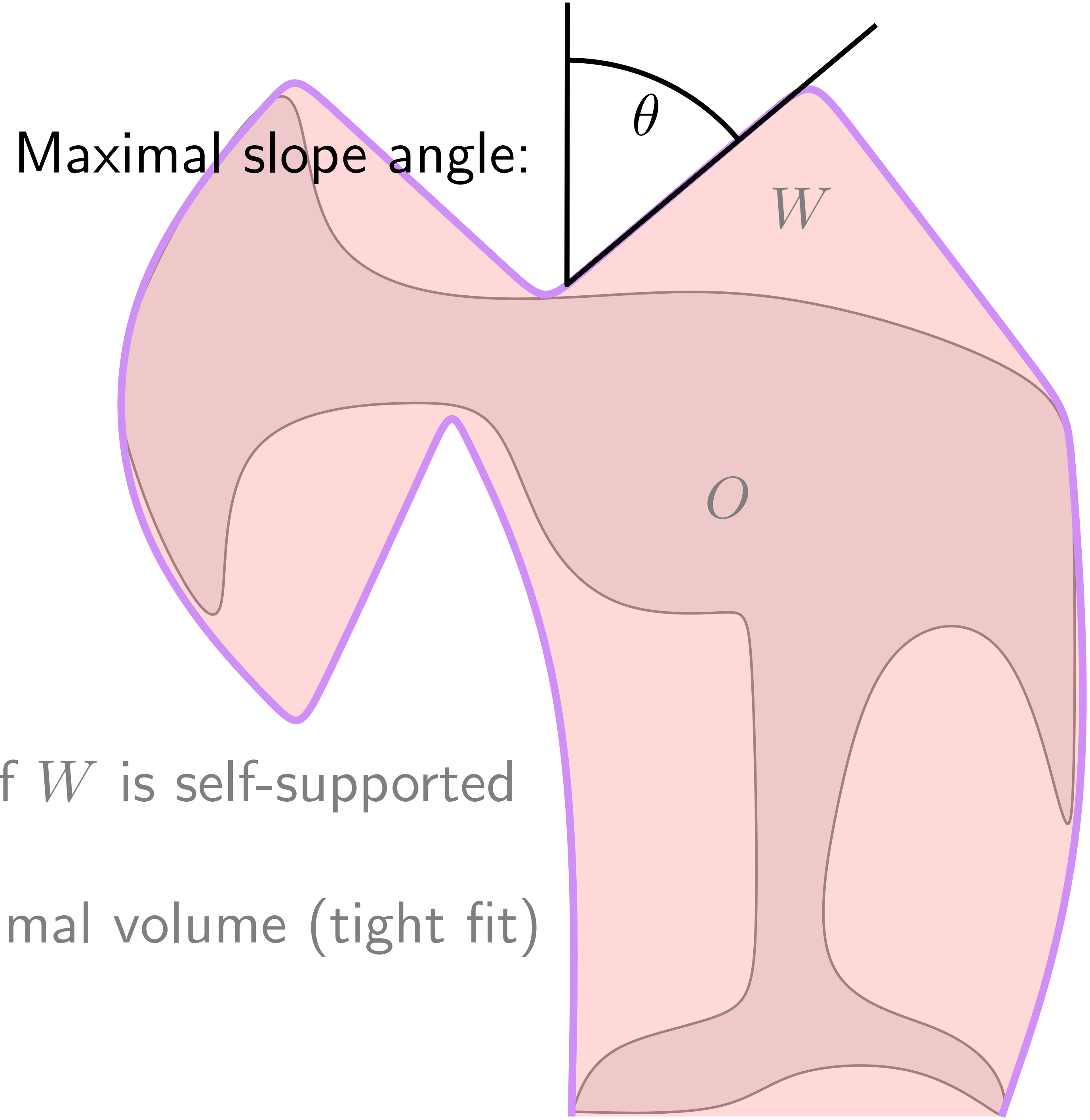

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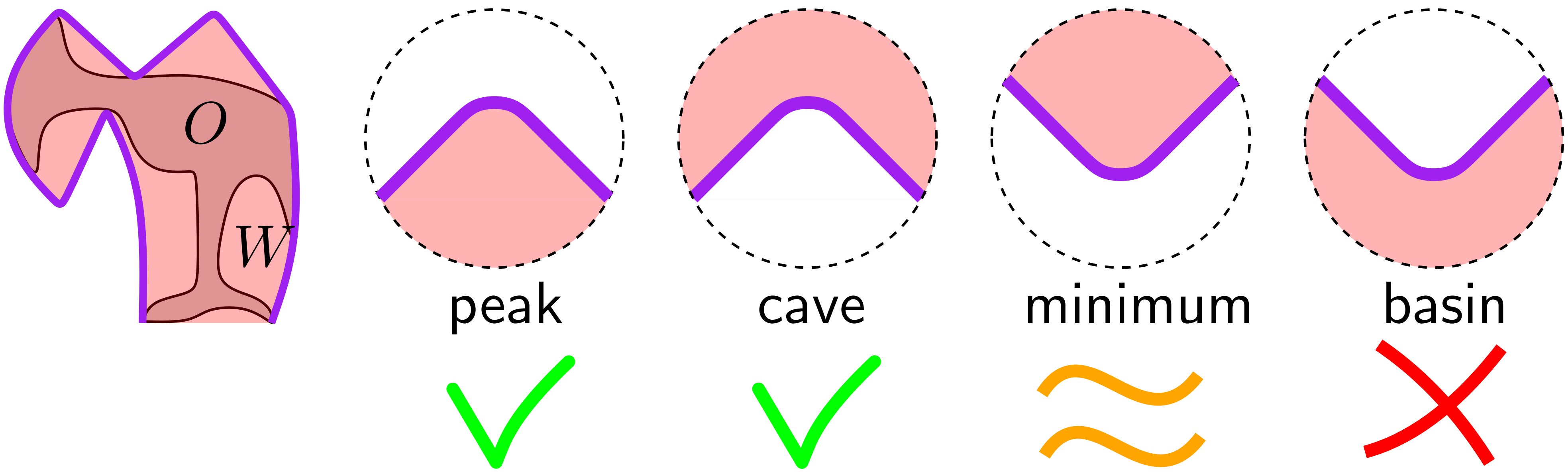

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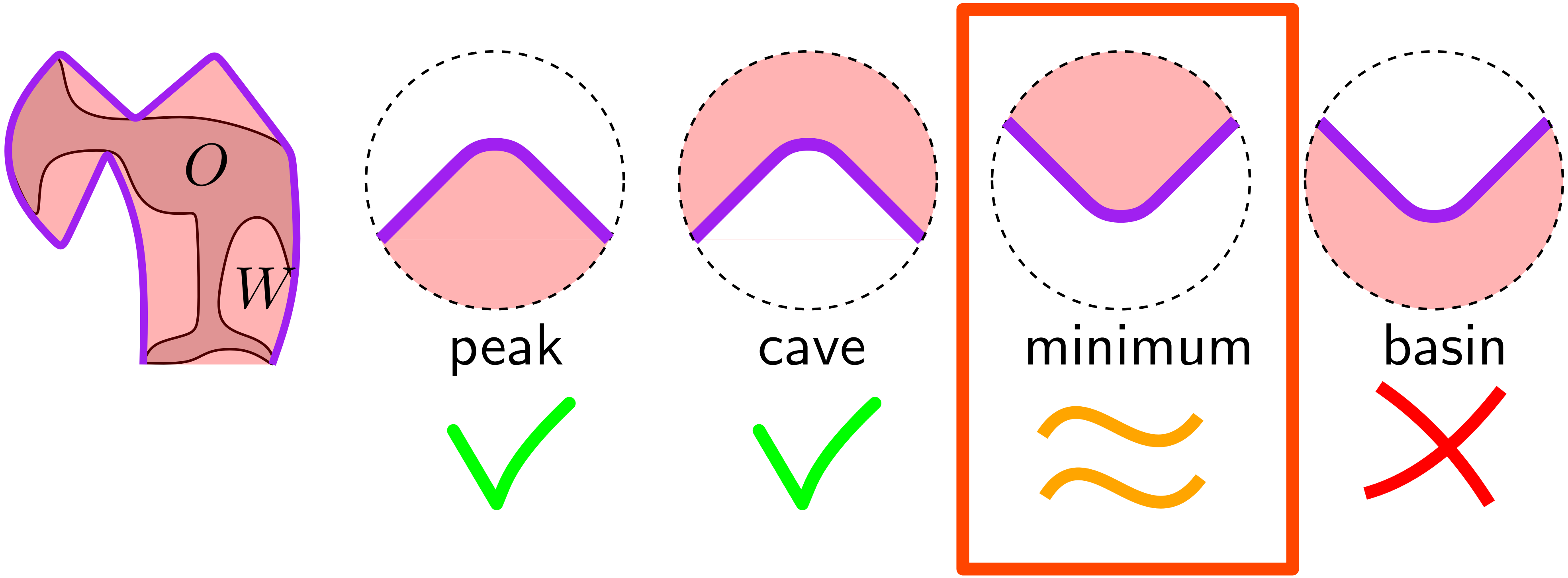


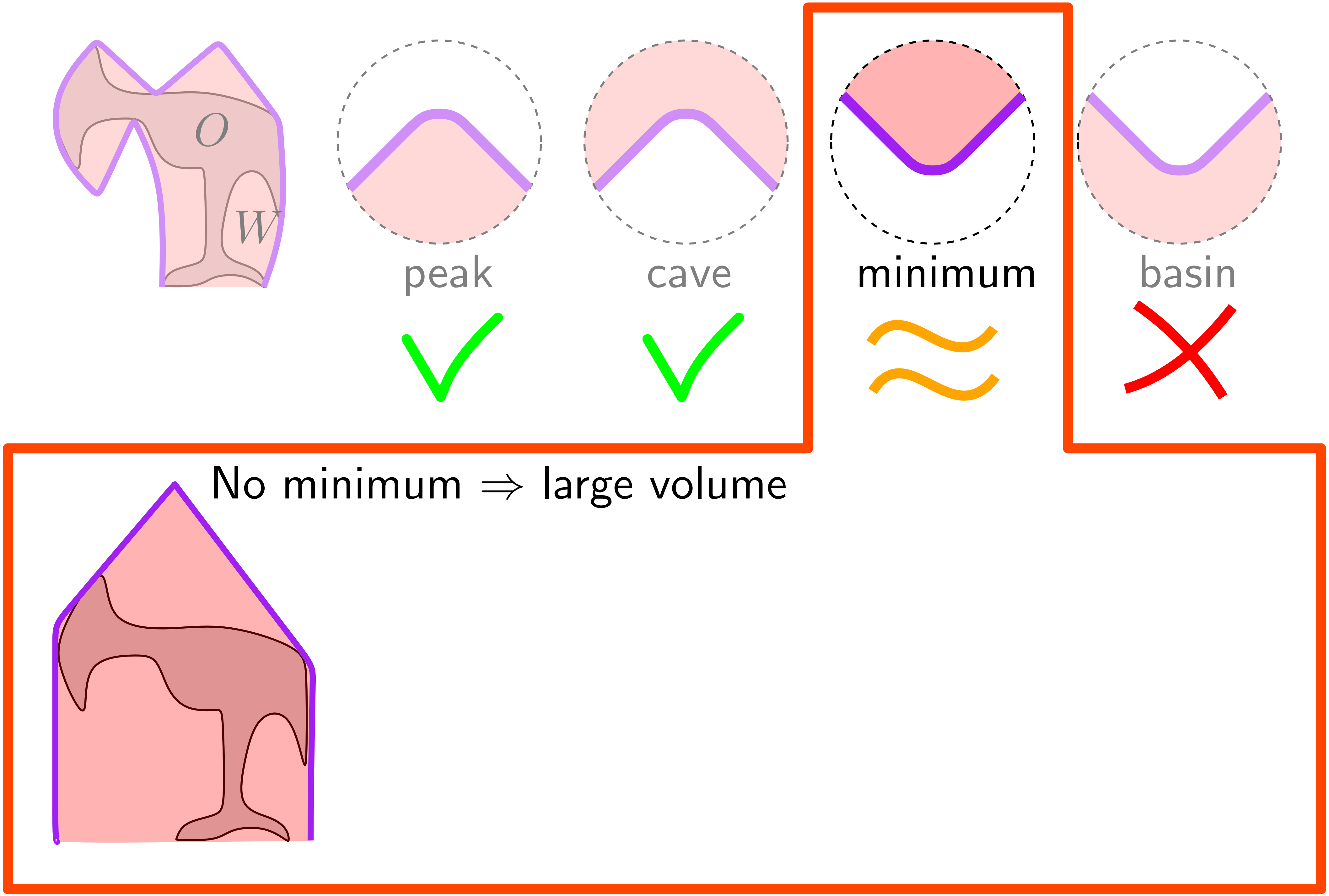
Trade-off:

Minimize volume of enclosure W

v.s.

Minimize amount of support structure

The problem



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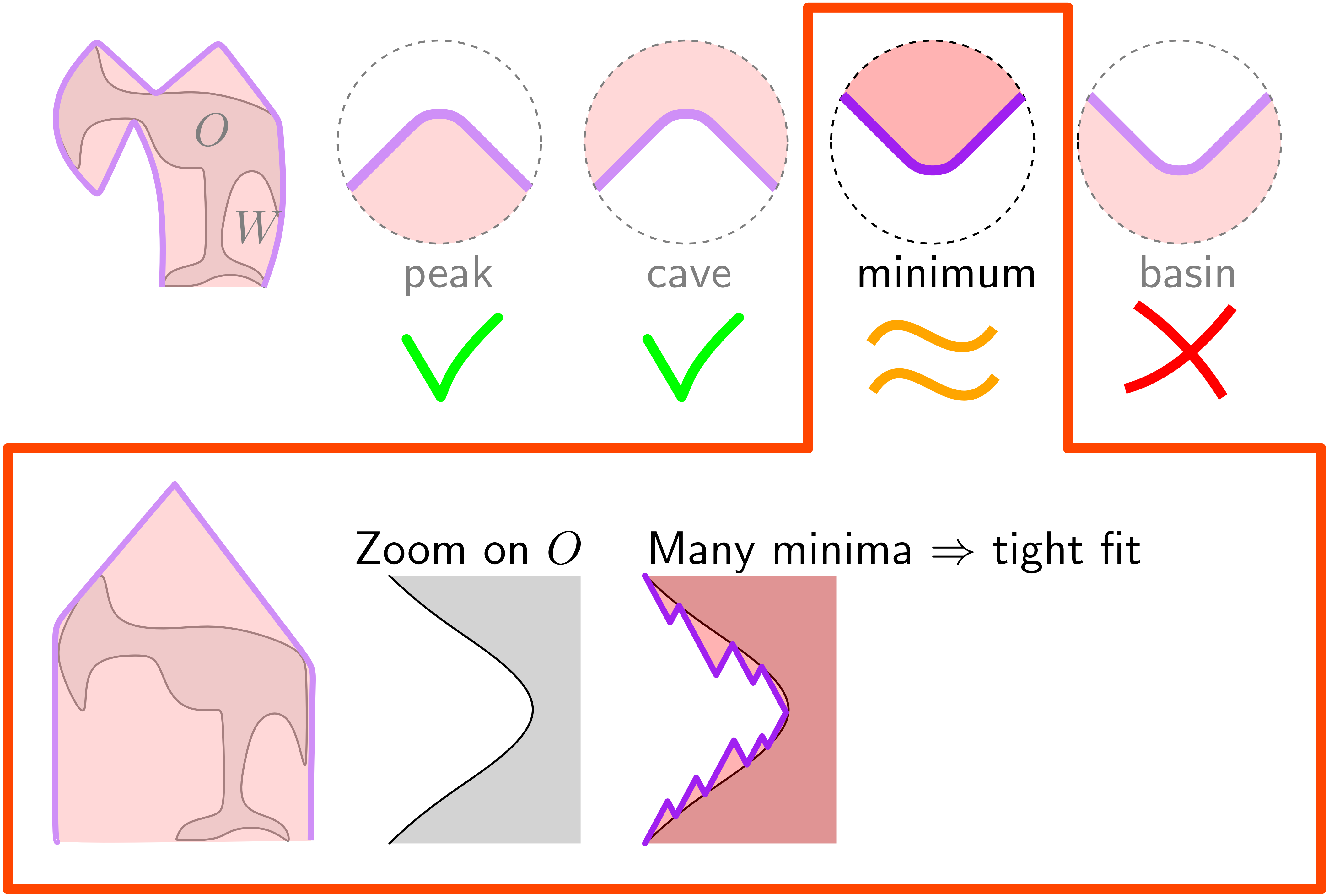

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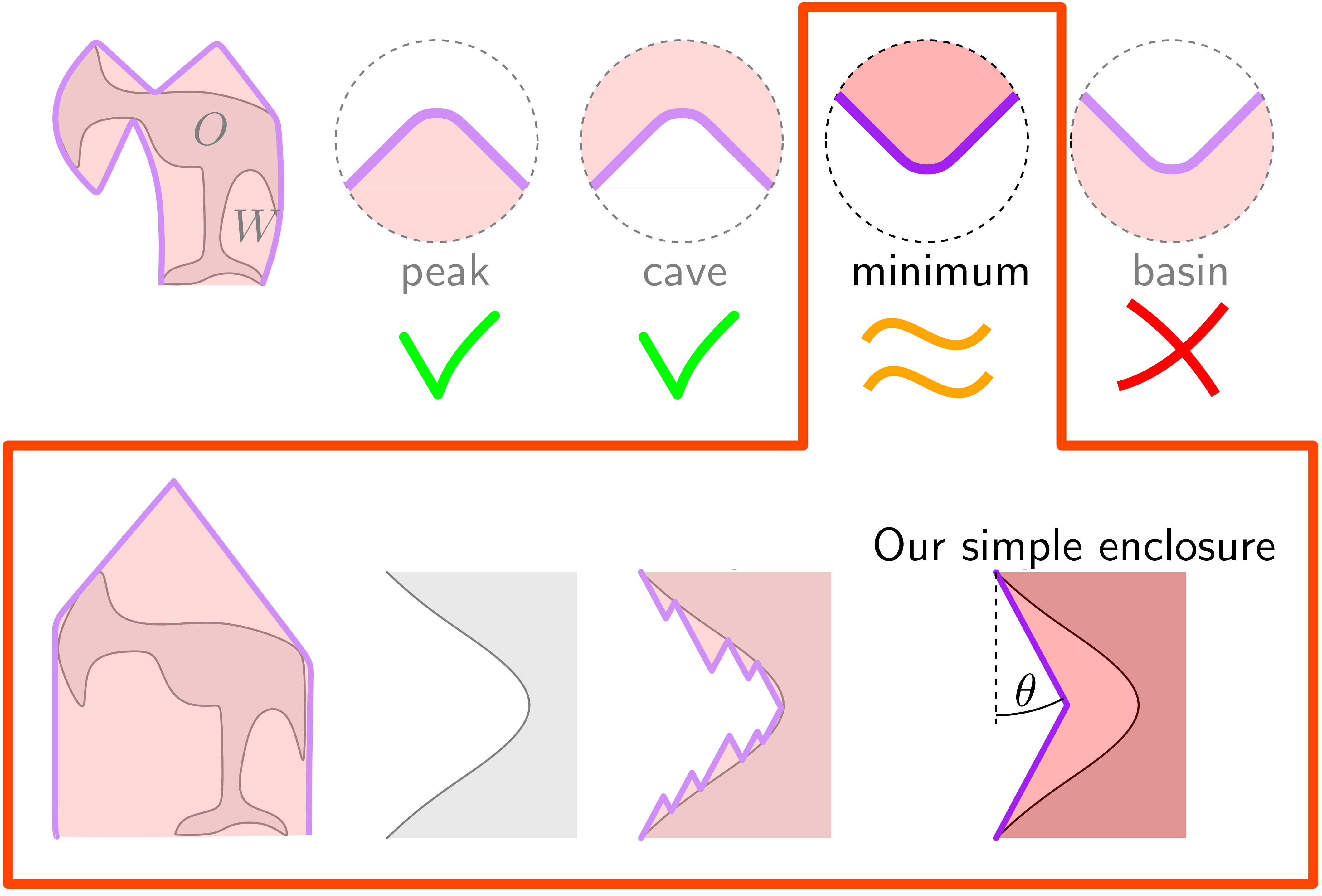
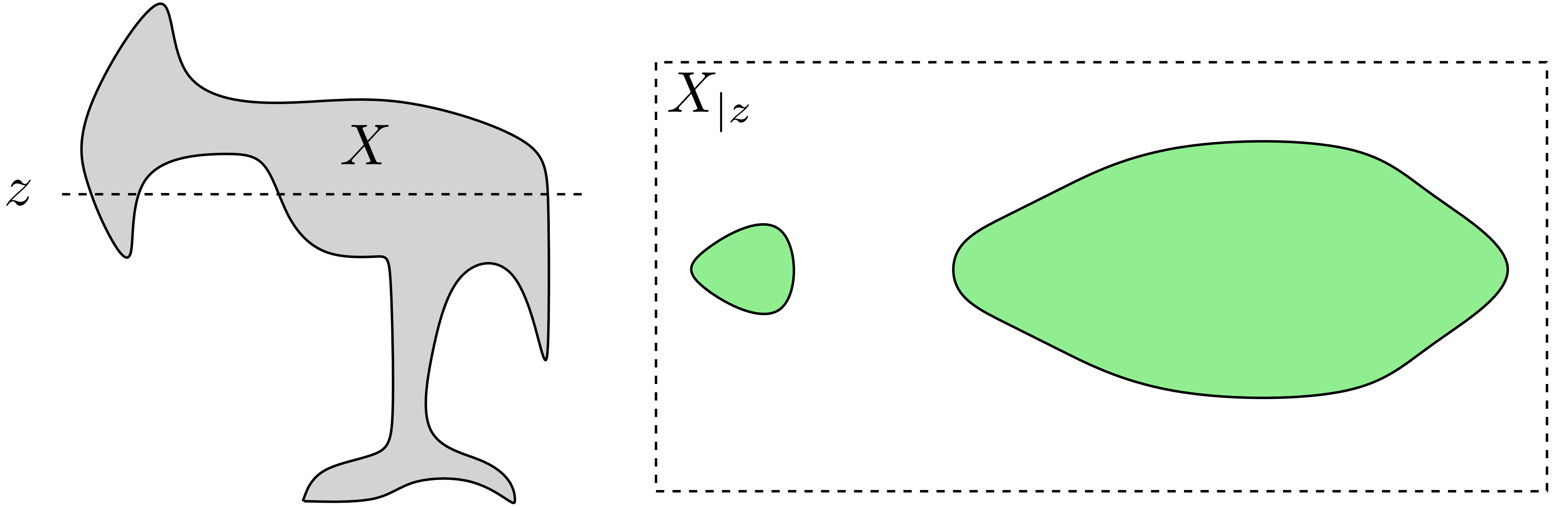


Modeling the simple enclosure

$X_{|z}$ is the slice of X at height z



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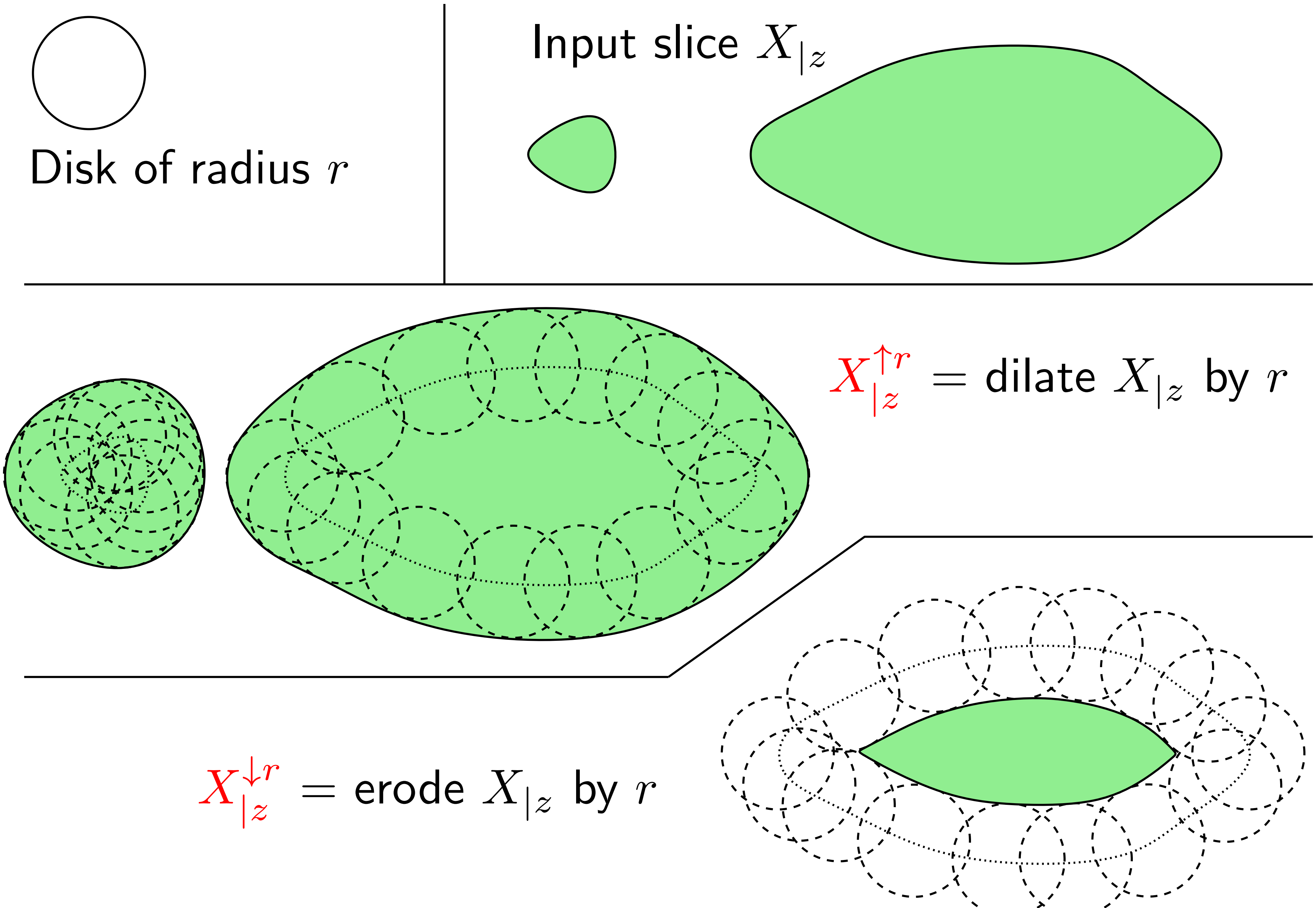
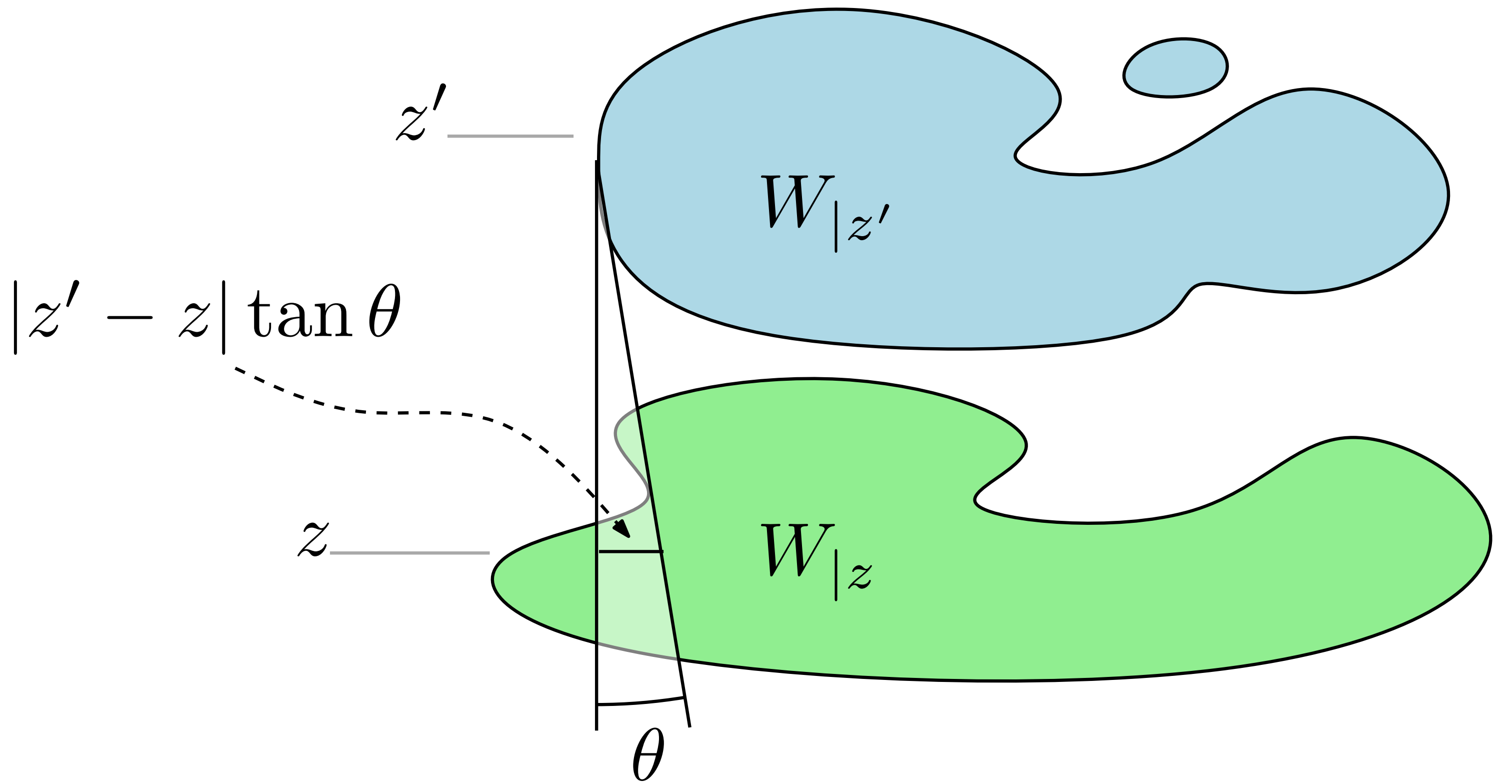


Modeling the simple enclosure

Given an object O, its simple enclosure W should satisfy:

$$\forall z \, \forall z' \quad W_{|z'}^{\downarrow |z'-z| \tan\theta} \subset W_{|z}$$



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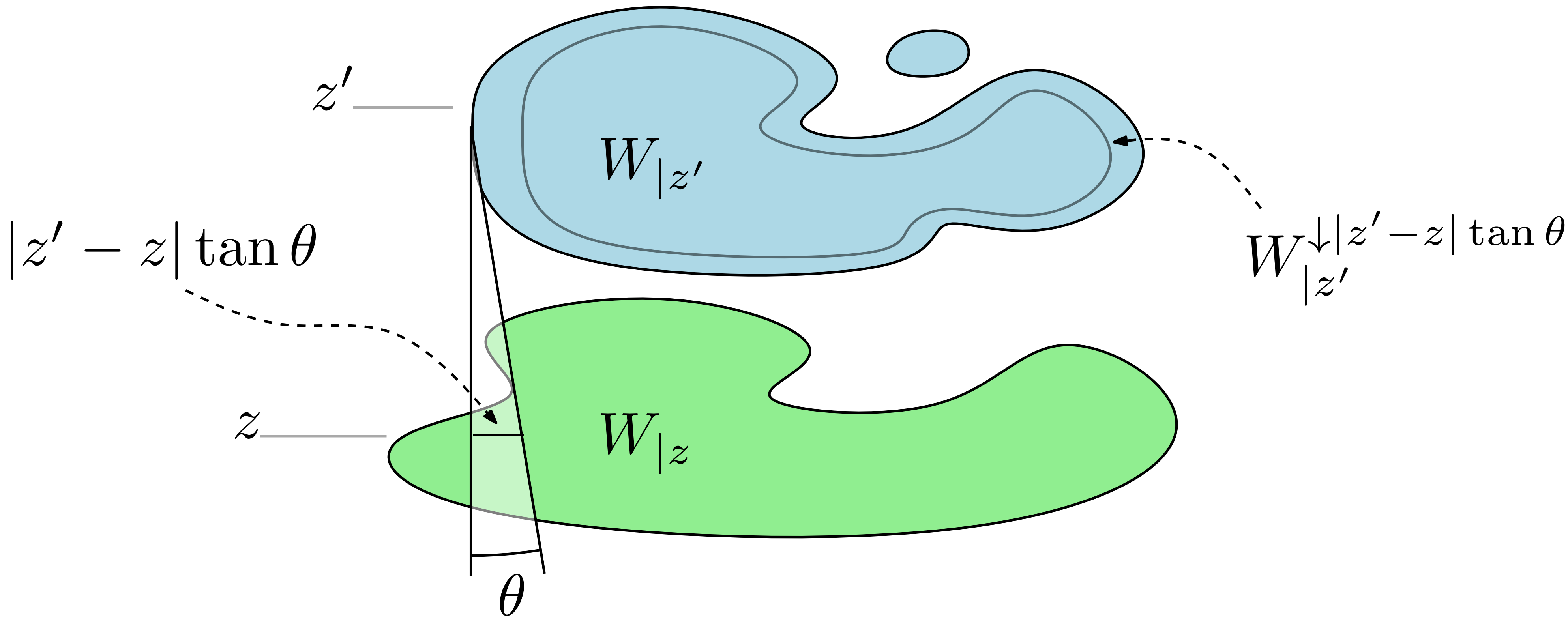

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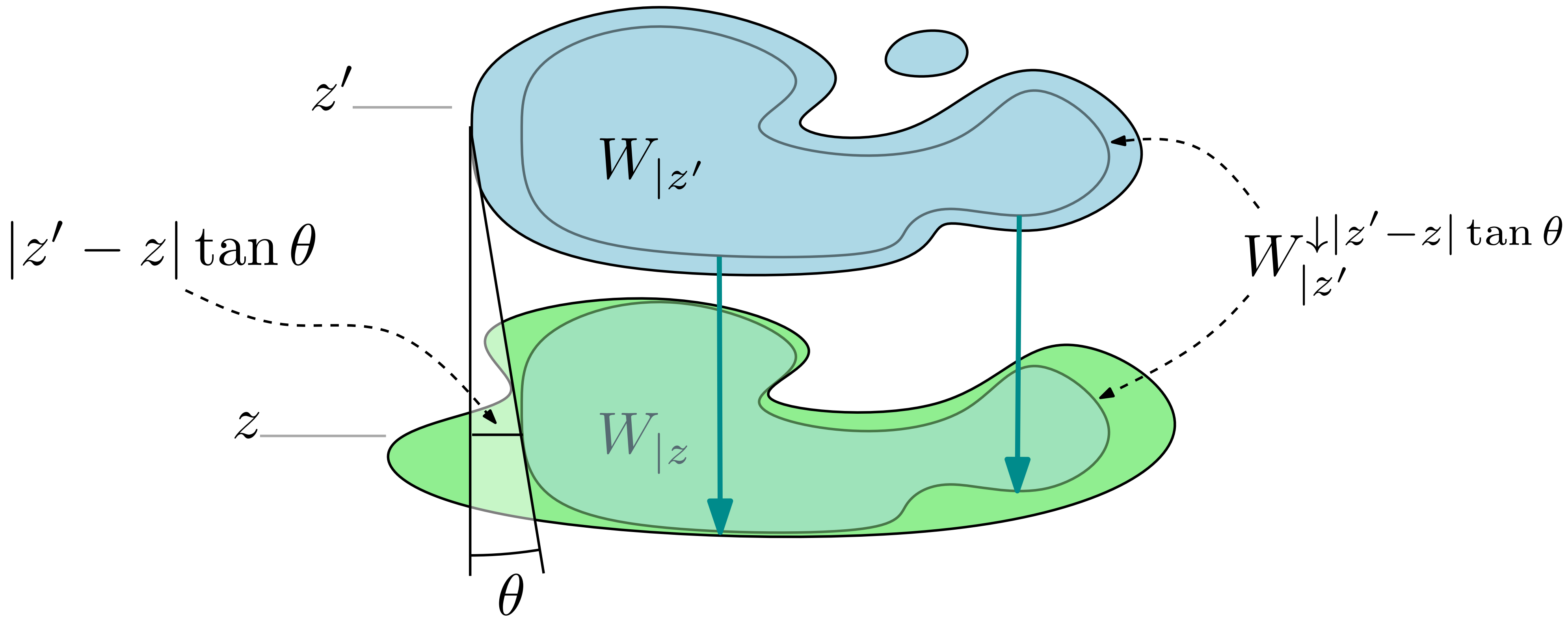


Modeling the simple enclosure

Given an object O, its simple enclosure W should satisfy:

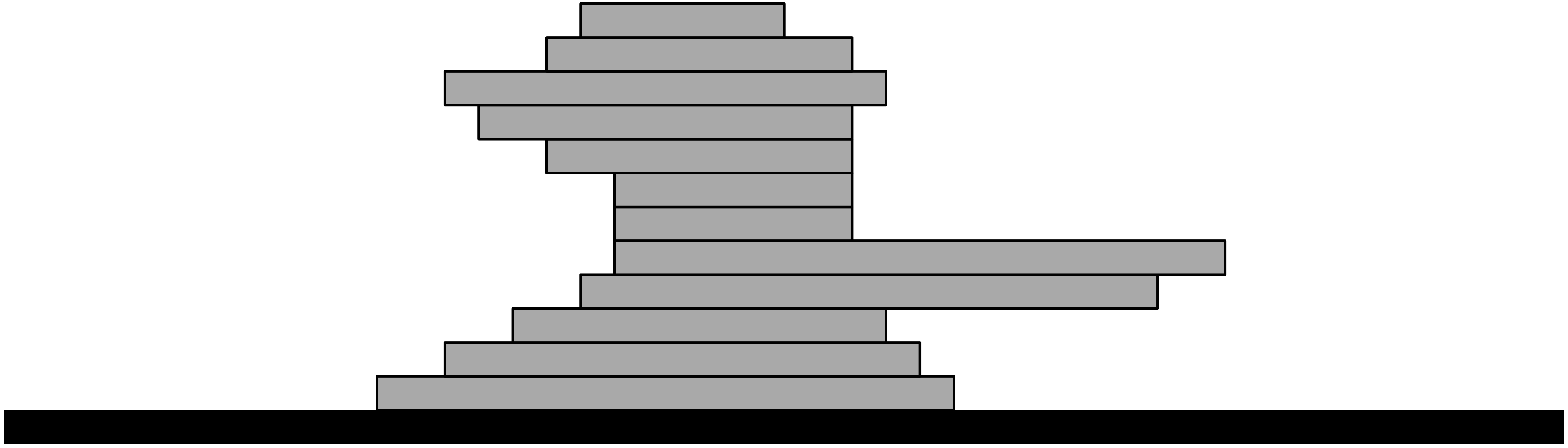
$$\forall z\, \forall z' \quad W_{|z'}^{\downarrow |z'-z| \tan\theta} \subset W_{|z}$$

Balances a tight fit and few local minima, and:

- no basin
- local minimum in $W \approx$ large overhangs in O

Adding constraints $(O \subset W)$ and (W has minimal volume) uniquely defines the enclosure volume.

Discrete setting: two passes over the slices



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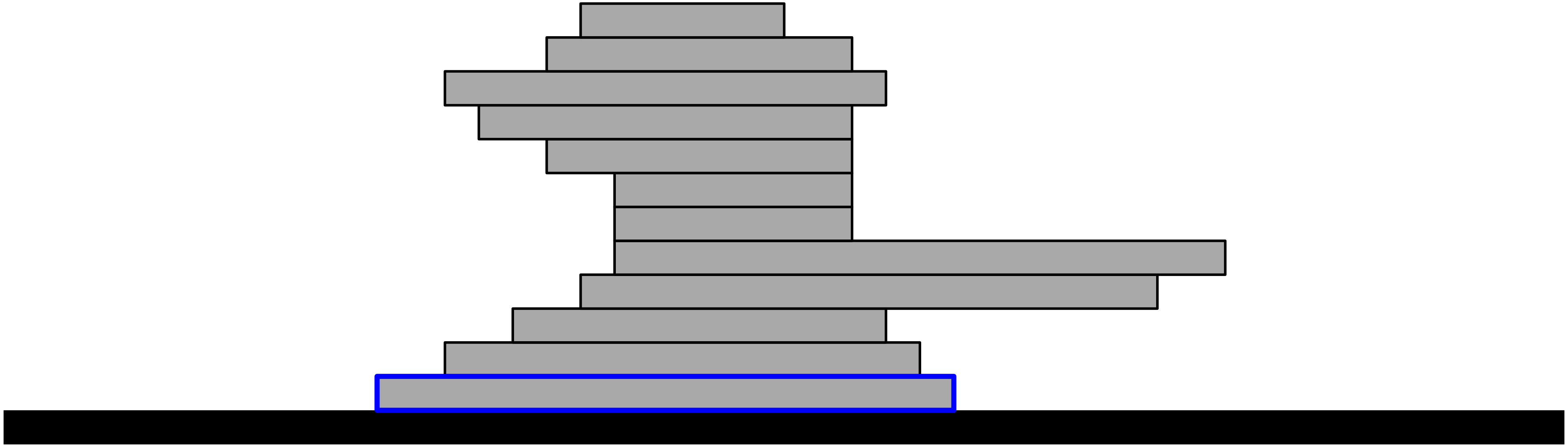

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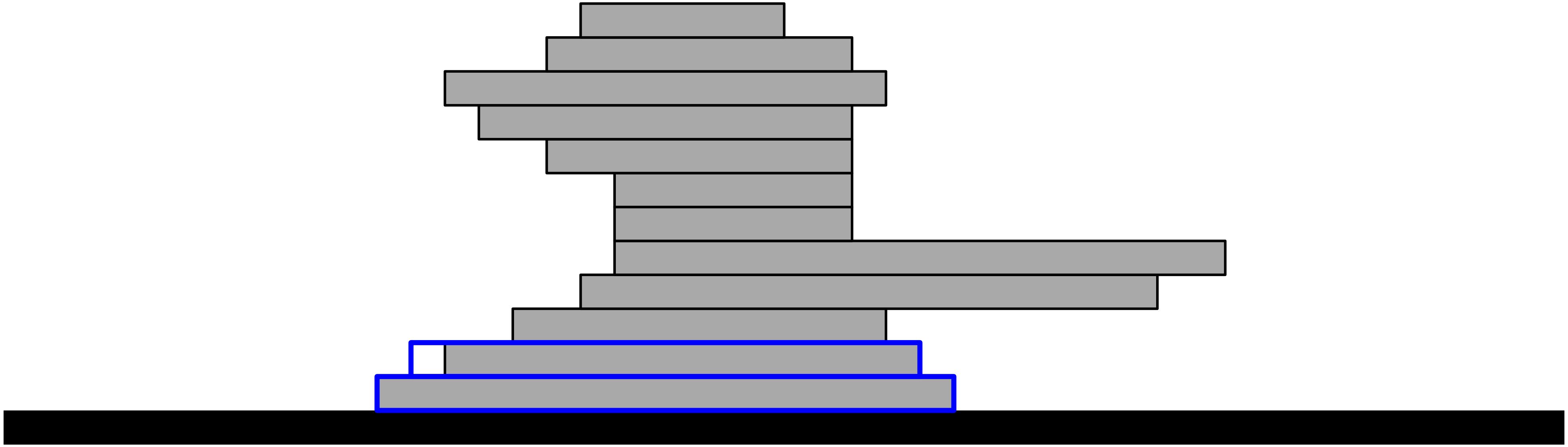

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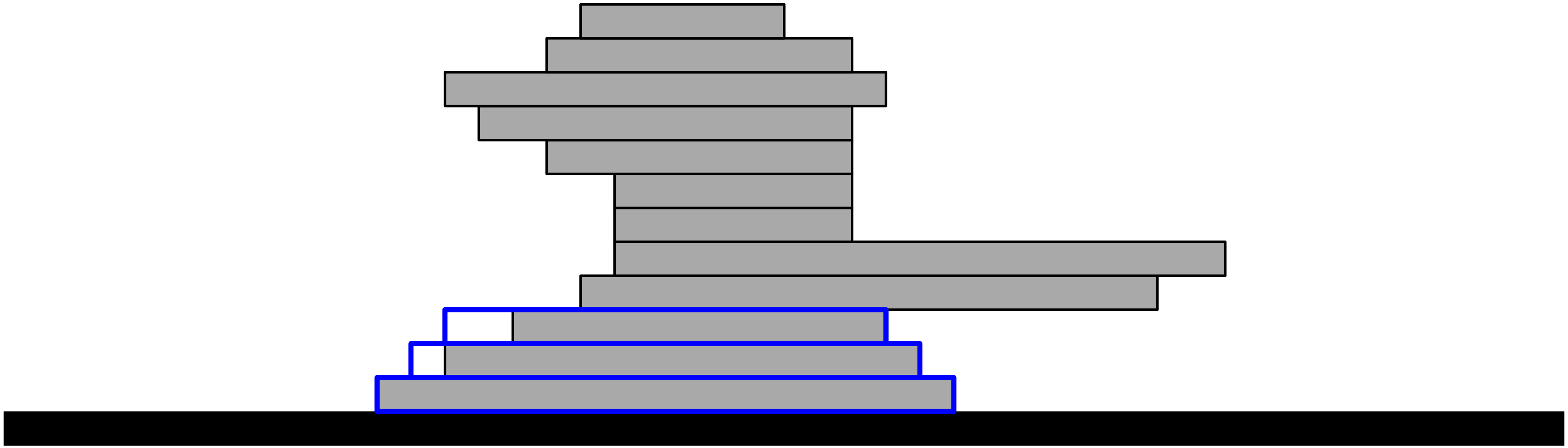

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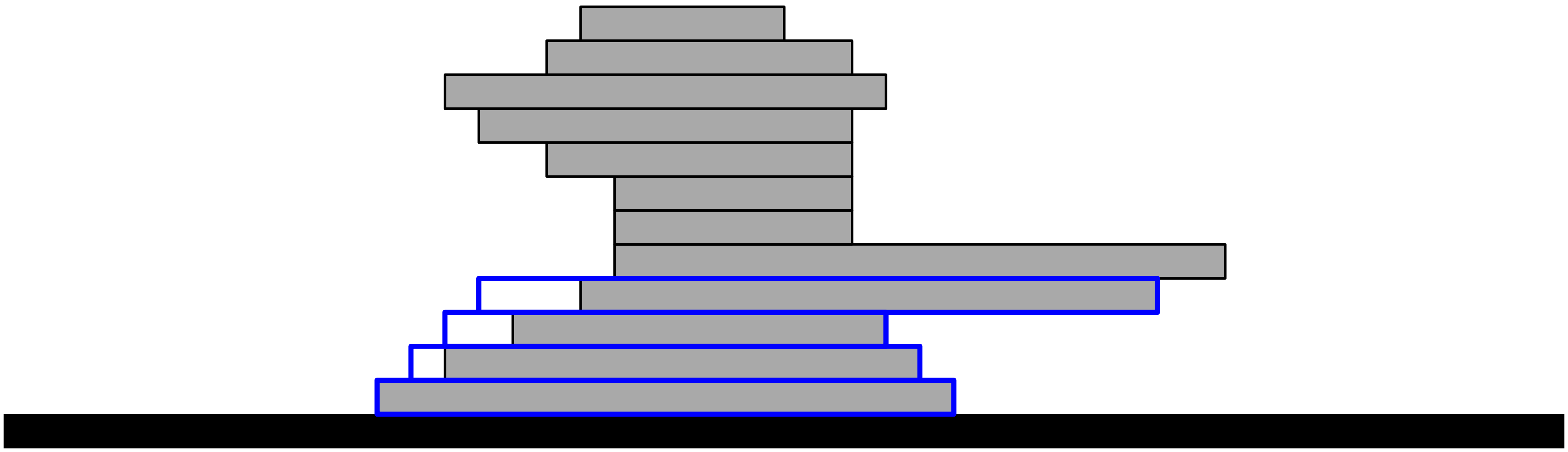

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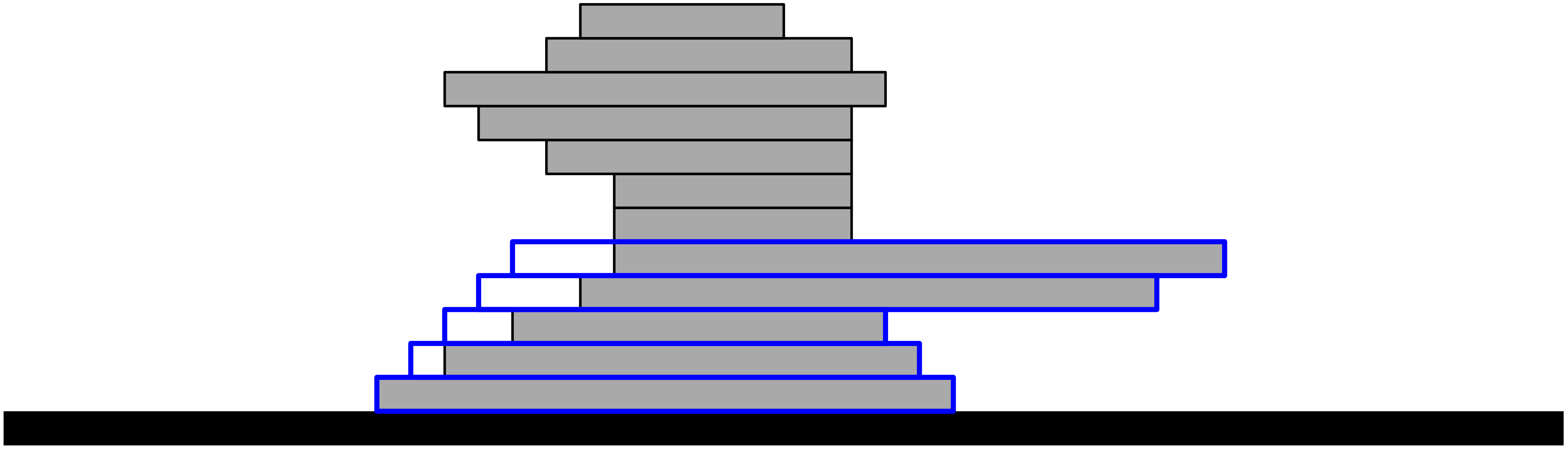

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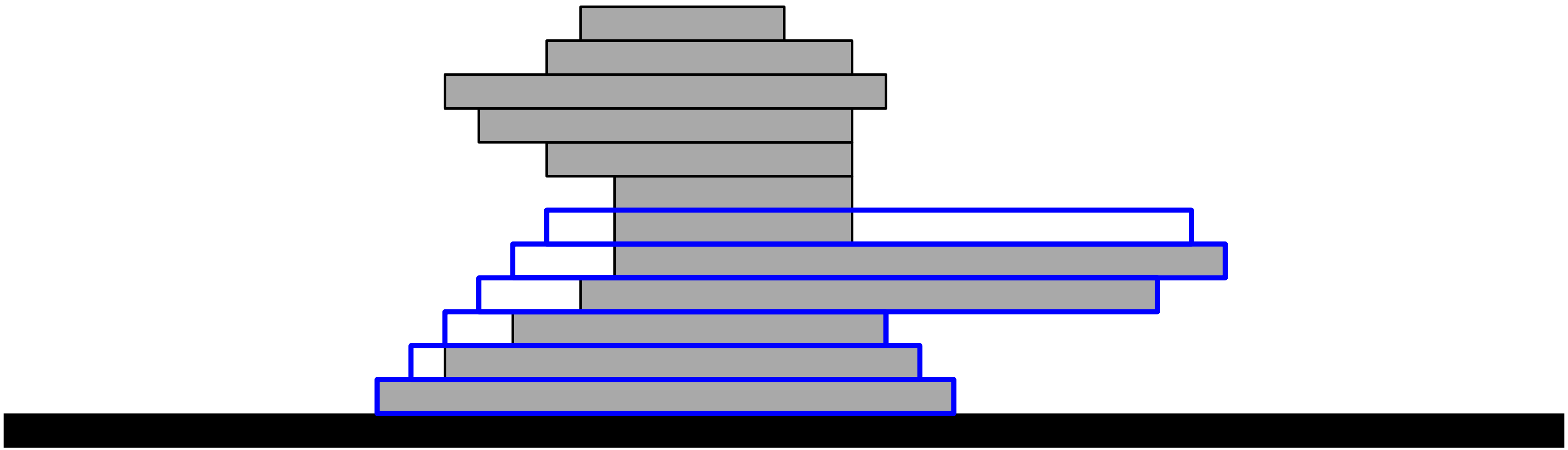

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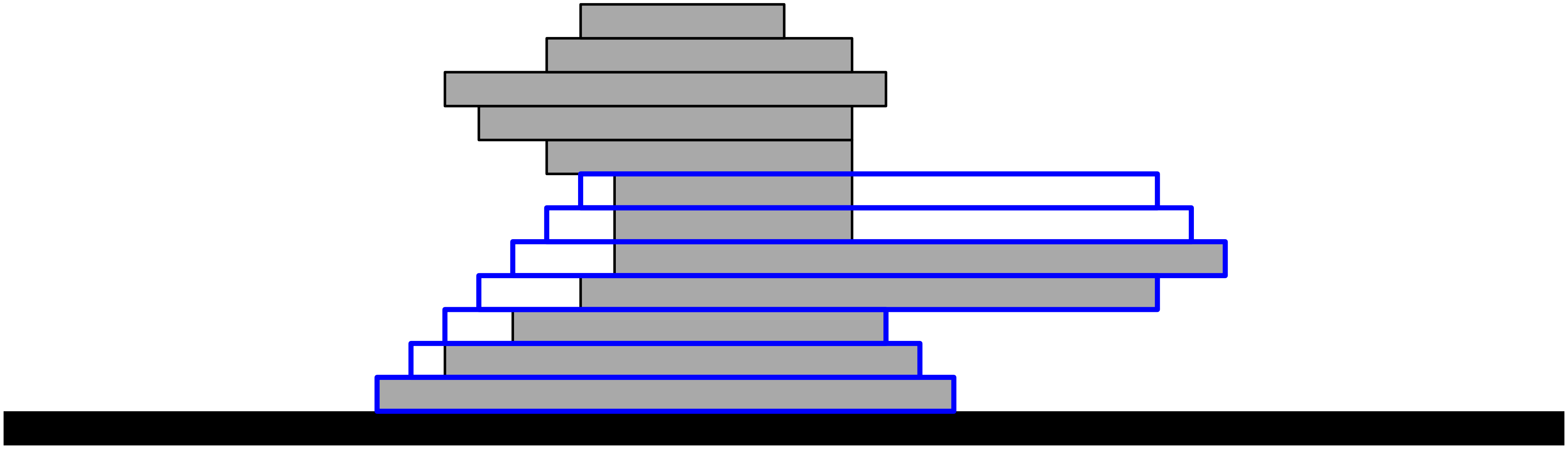

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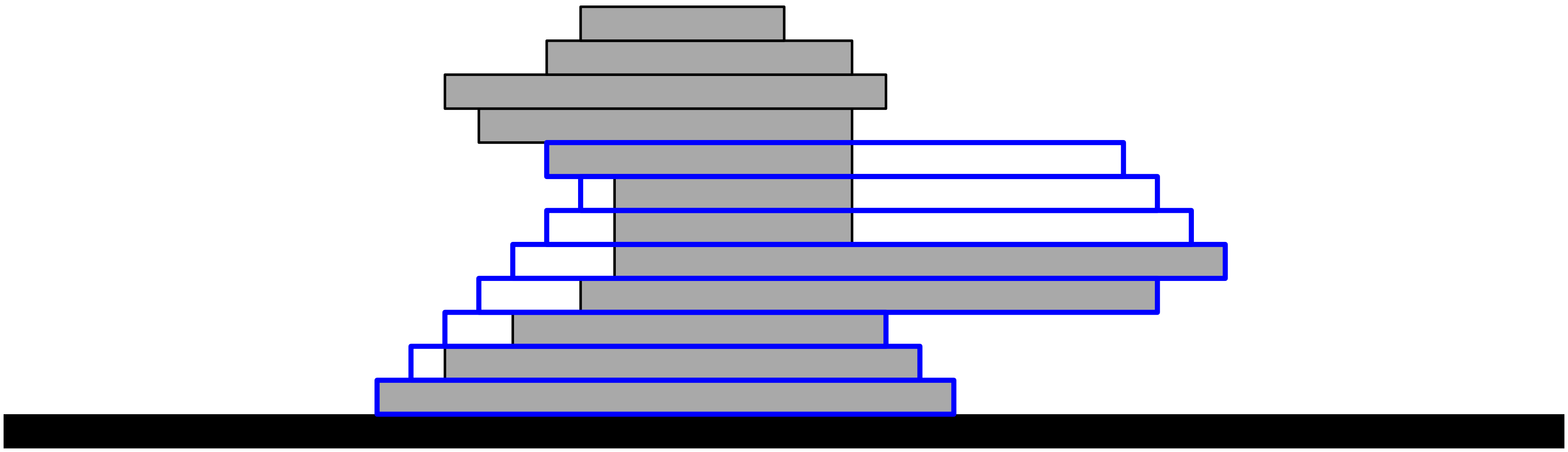

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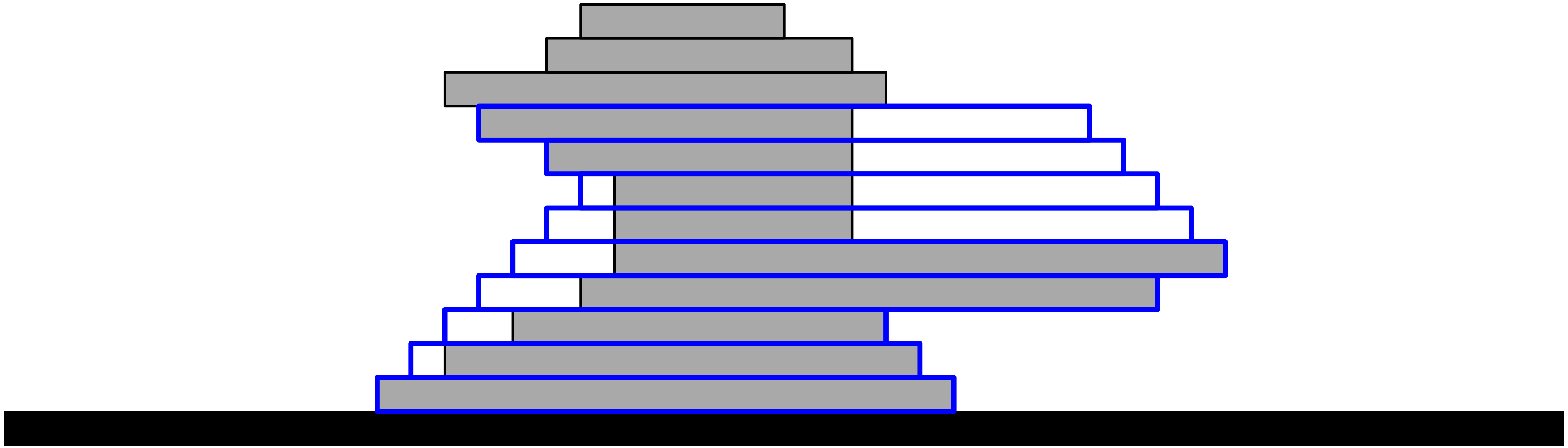

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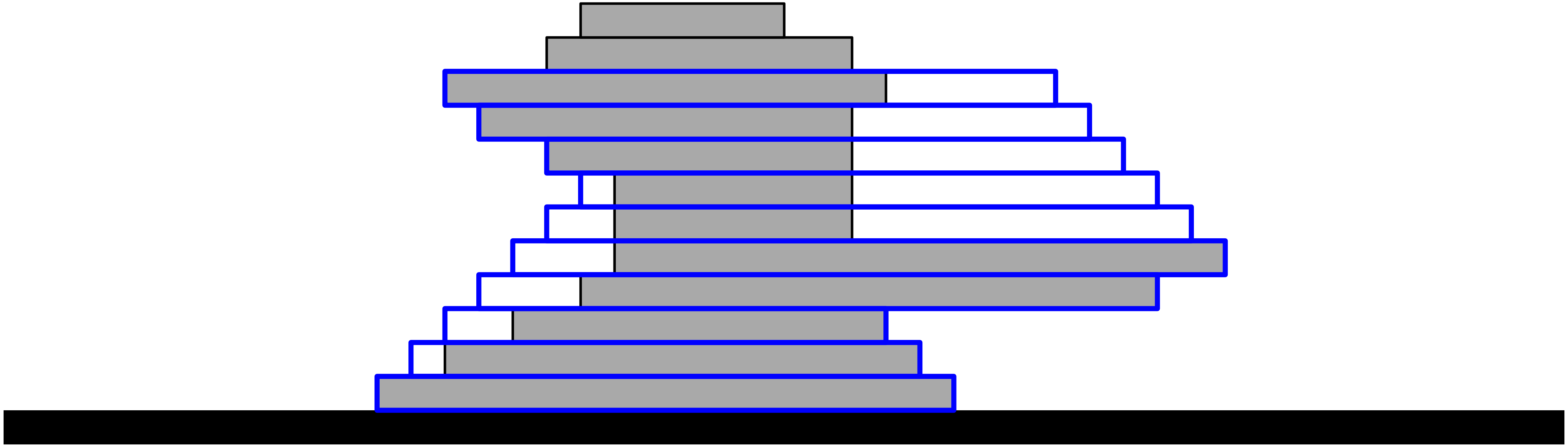

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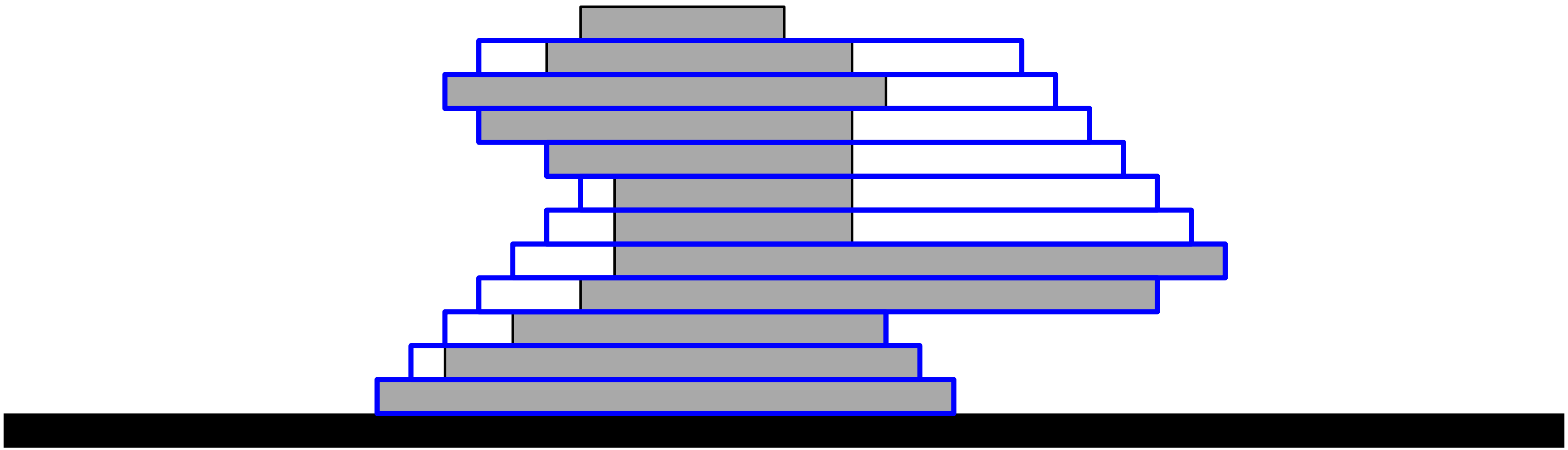

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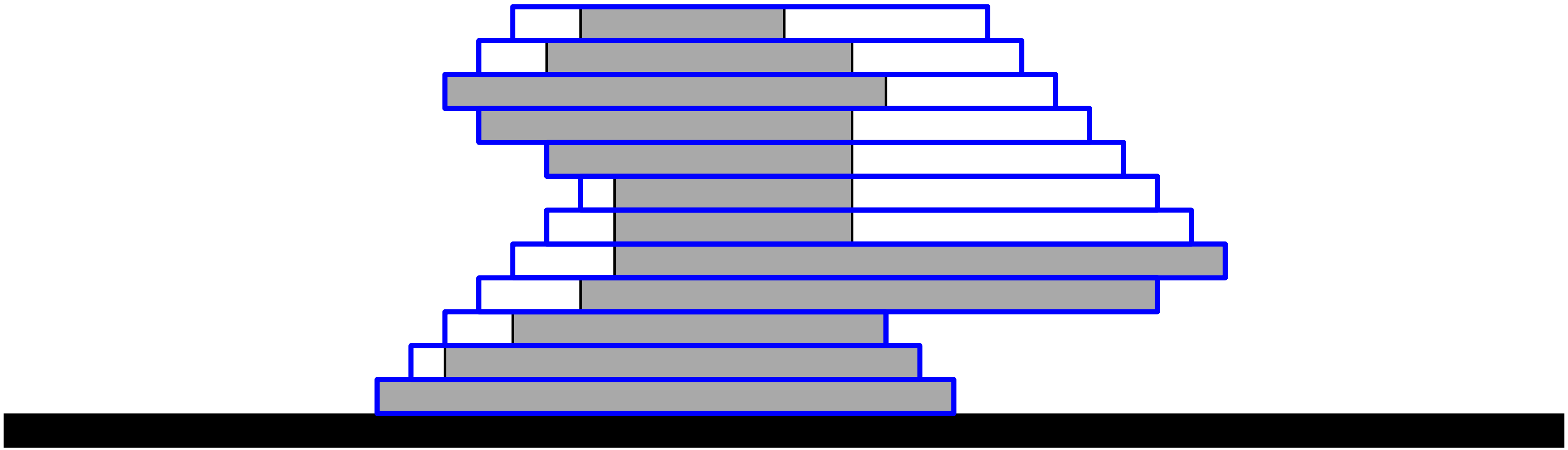

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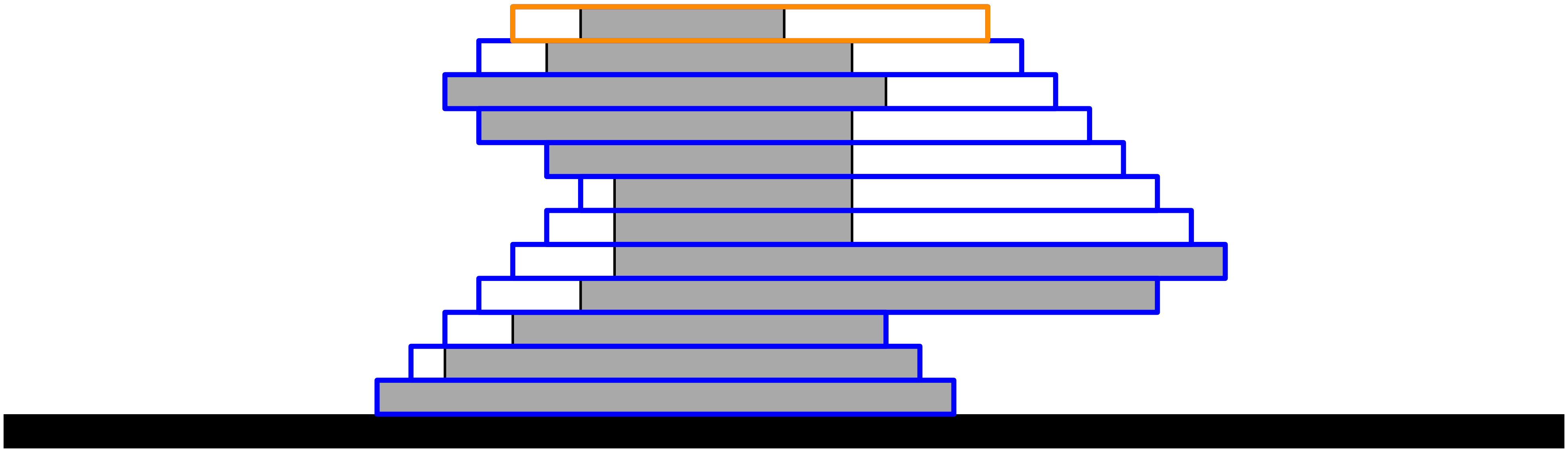

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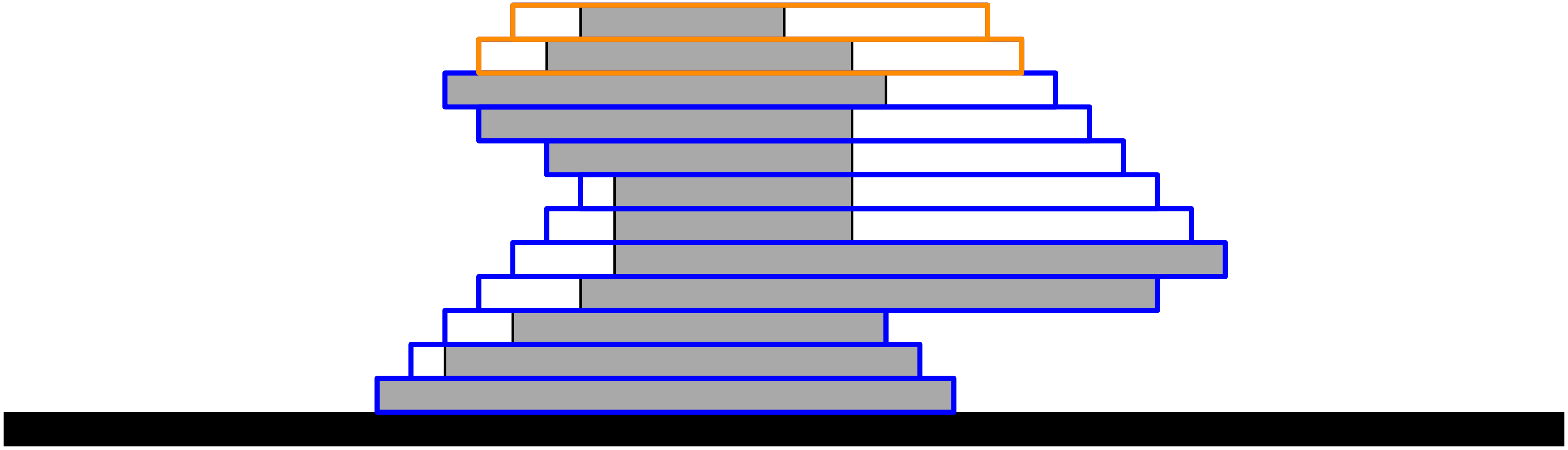

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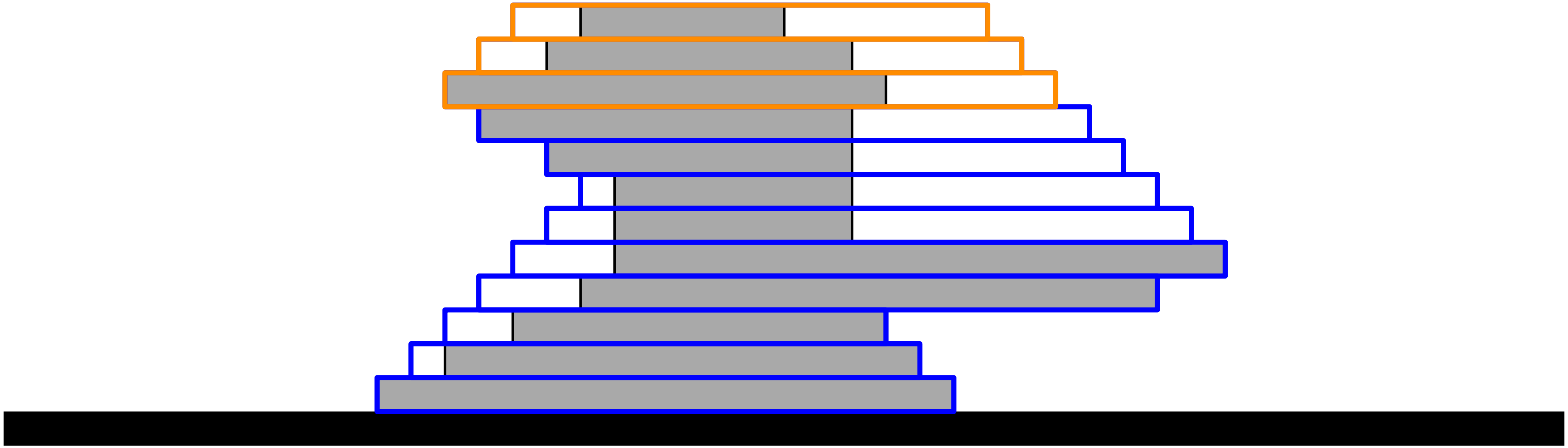

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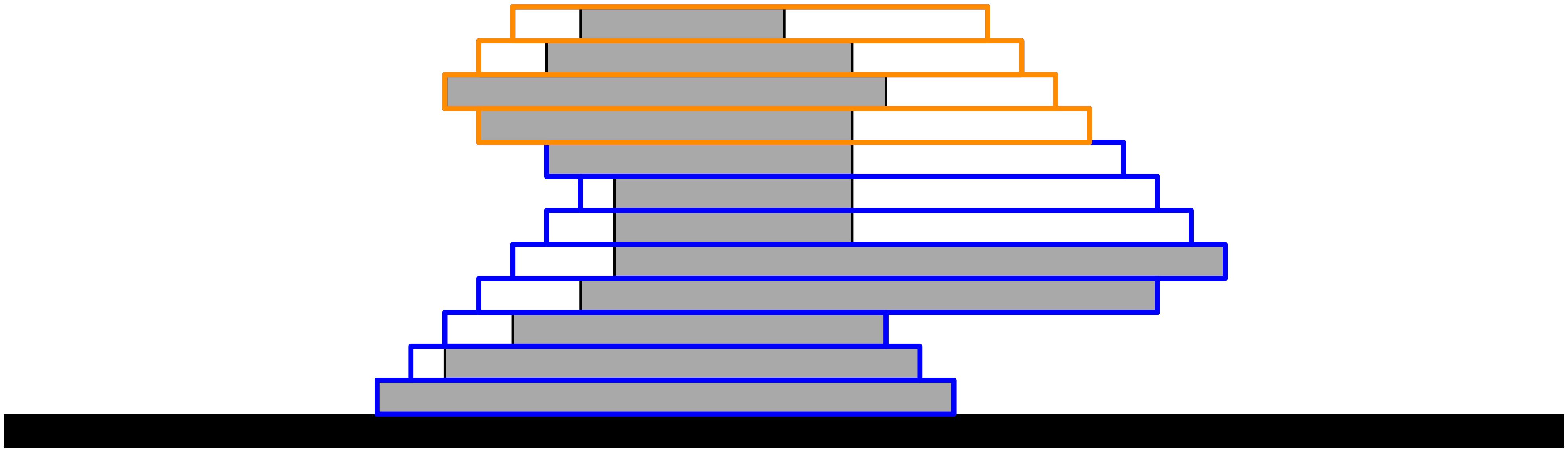

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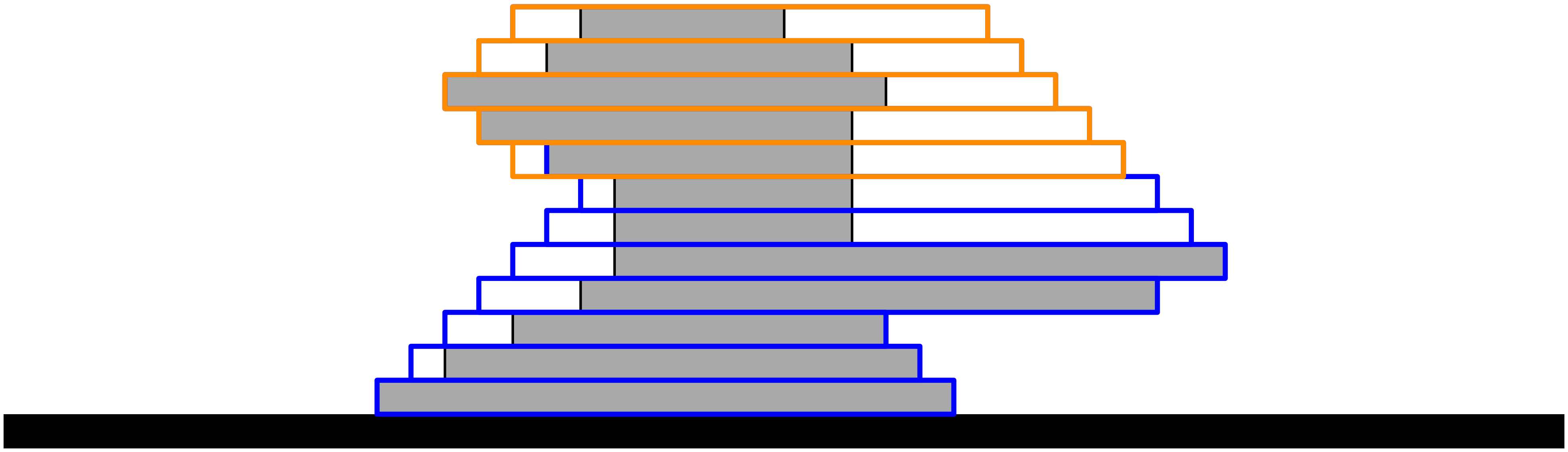

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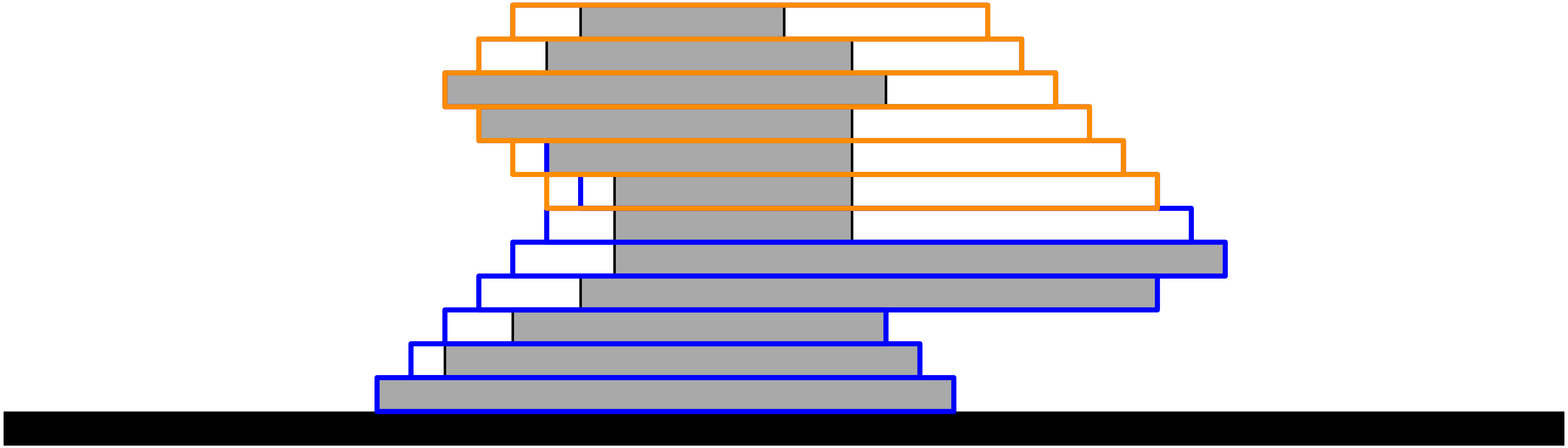

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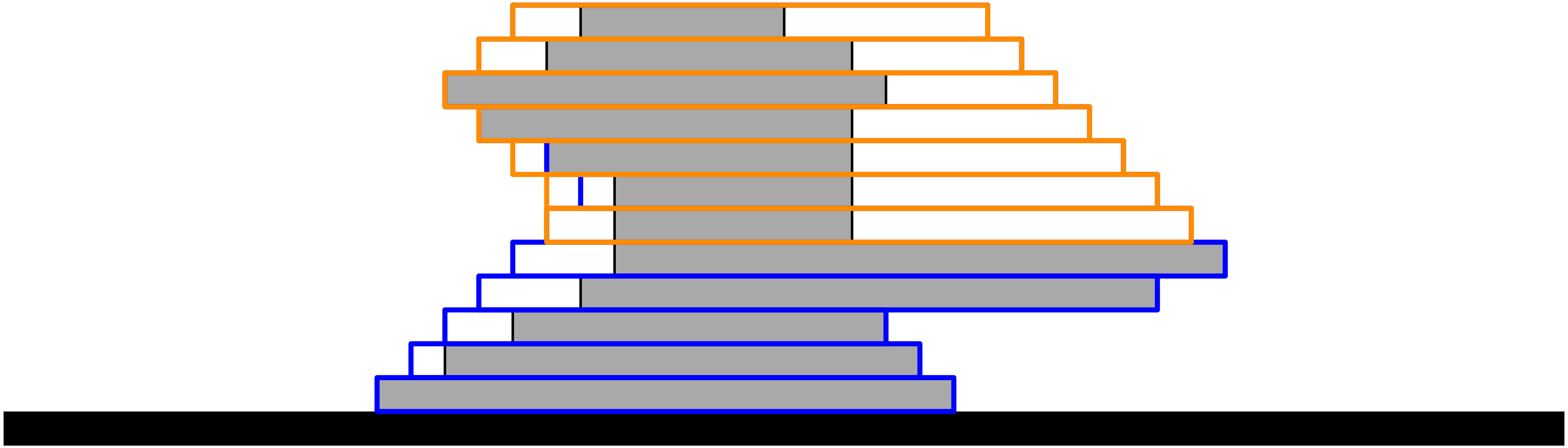

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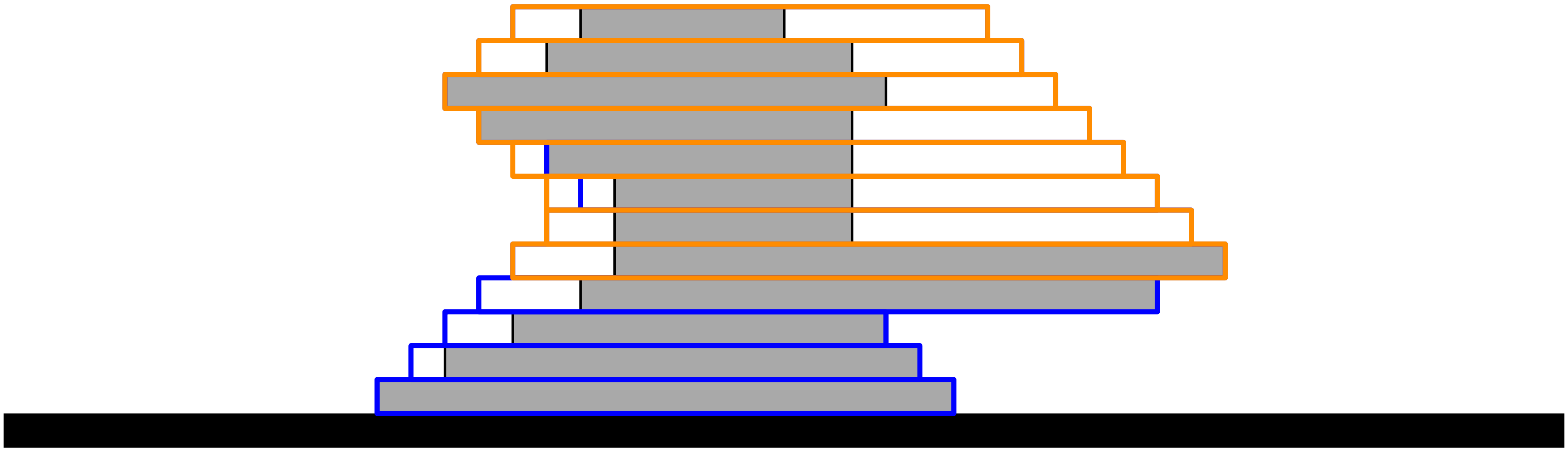

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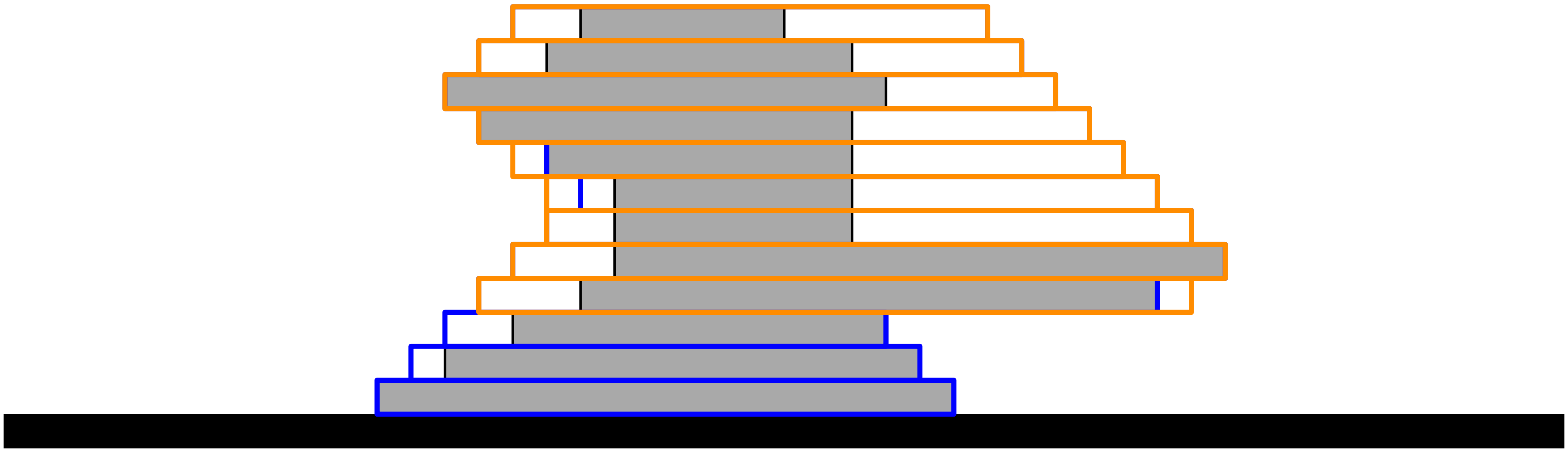

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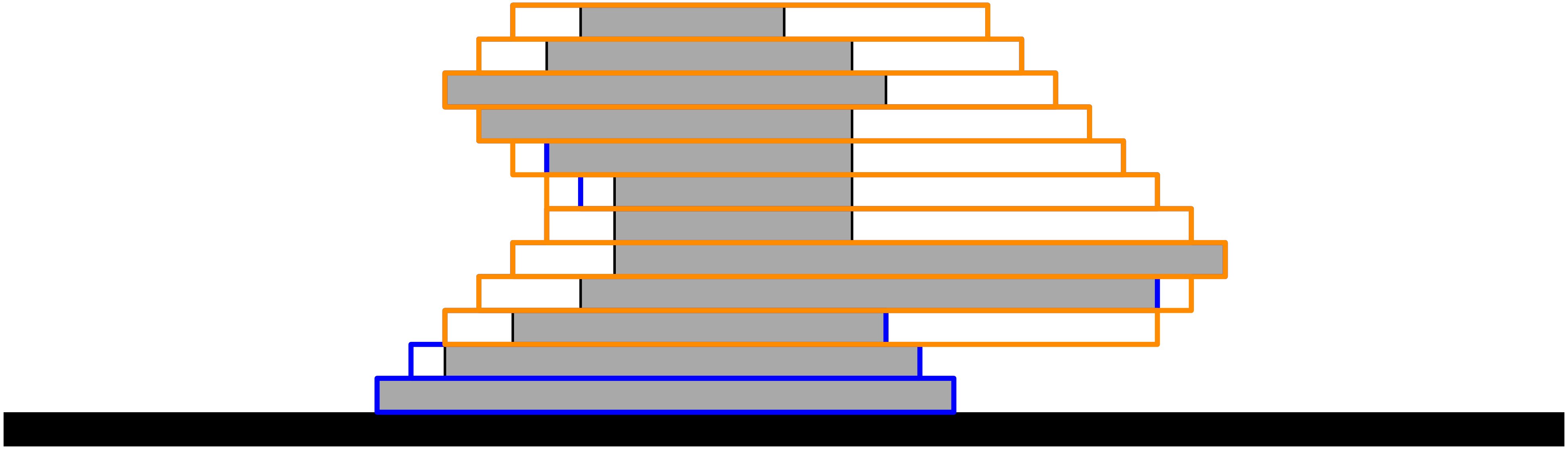

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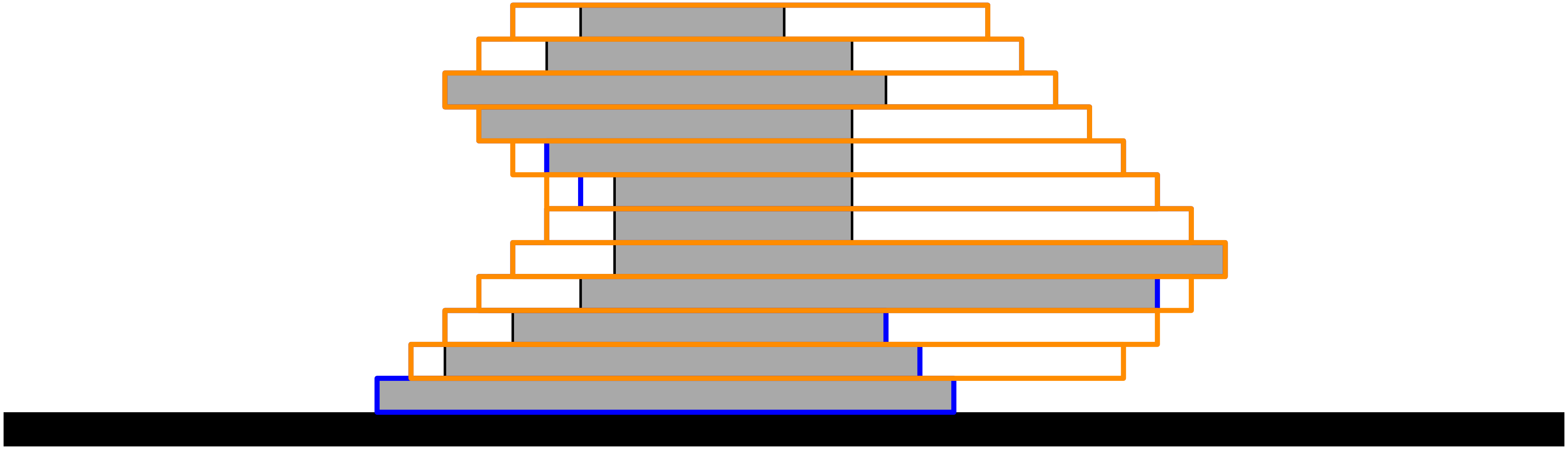

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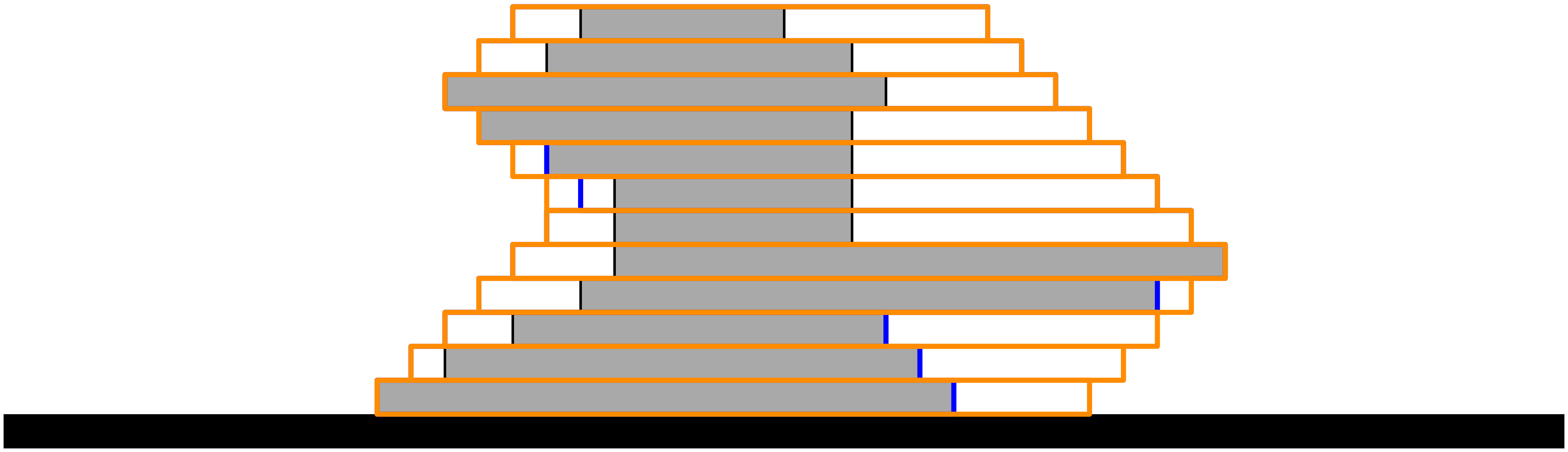


Modeling the simple enclosure in two passes

function SimpleEnclosure(O)
  temp ← PropagateUp(O)
  W ← PropagateDown(temp)
  return the enclosure W

---

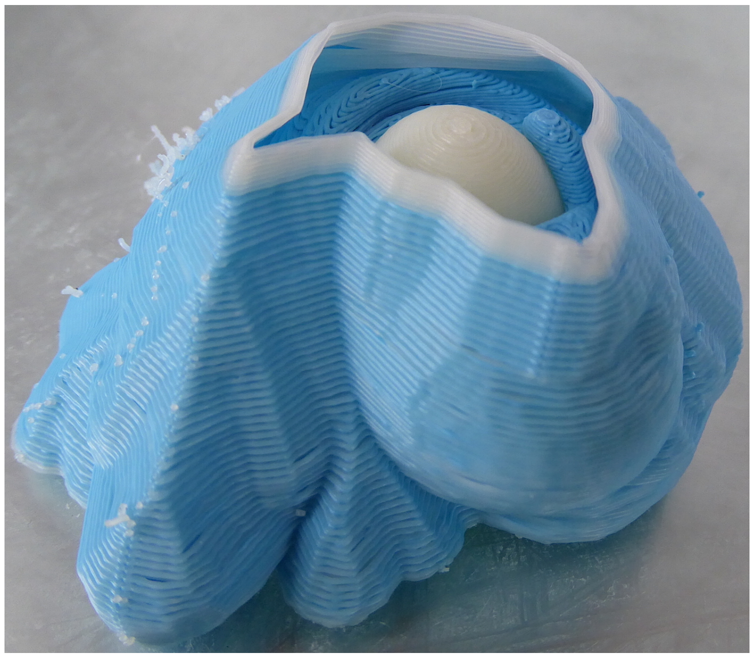
function PropagateUp(O) ▷ The input O is made of $n+1$ slices
  $V_{|0} \leftarrow O_{|0}$ ▷ Initialization of the bottom slice
  for $i = 1$ to n **do** ▷ Propagate from bottom to top
    $V_{|i} \leftarrow O_{|i} \cup V_{|i-1}^{\downarrow \Delta \tan \theta}$
  return the volume V

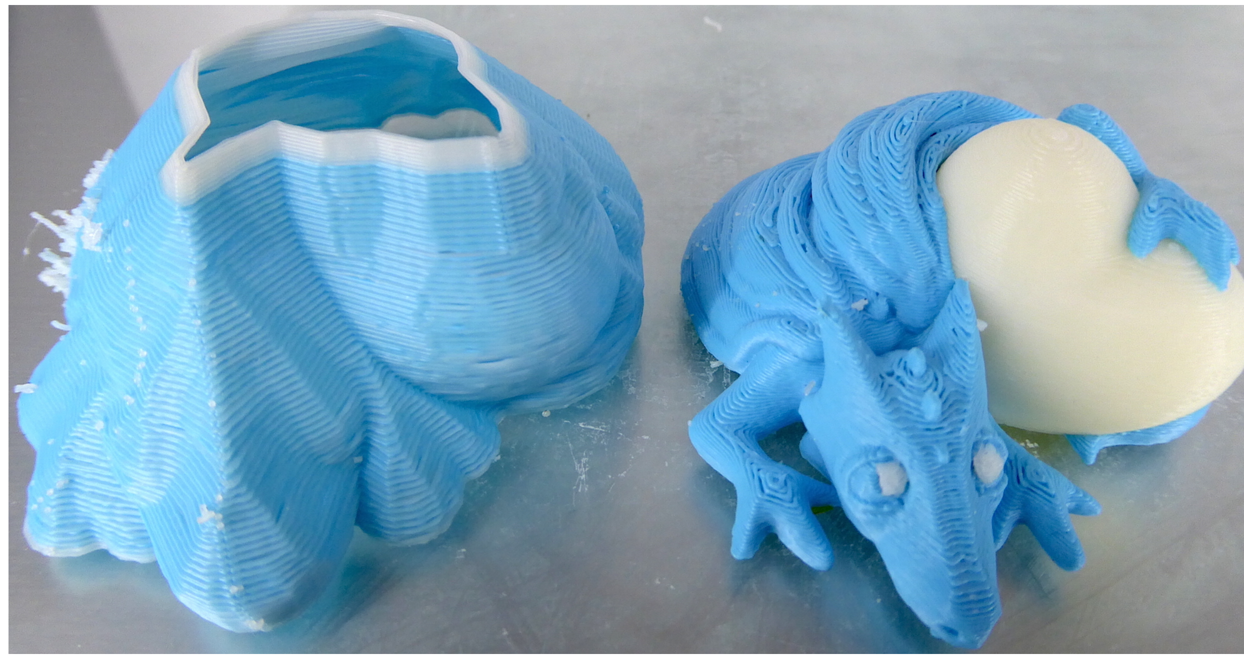
---

function PropagateDown(O)
  $V_{|n} \leftarrow O_{|n}$ ▷ Initialization of the top slice
  for $i = n-1$ down to 0 **do** ▷ Propagate from top to bottom
    $V_{|i} \leftarrow O_{|i} \cup V_{|i+1}^{\downarrow \Delta \tan \theta}$
  return the volume V

Protective wall

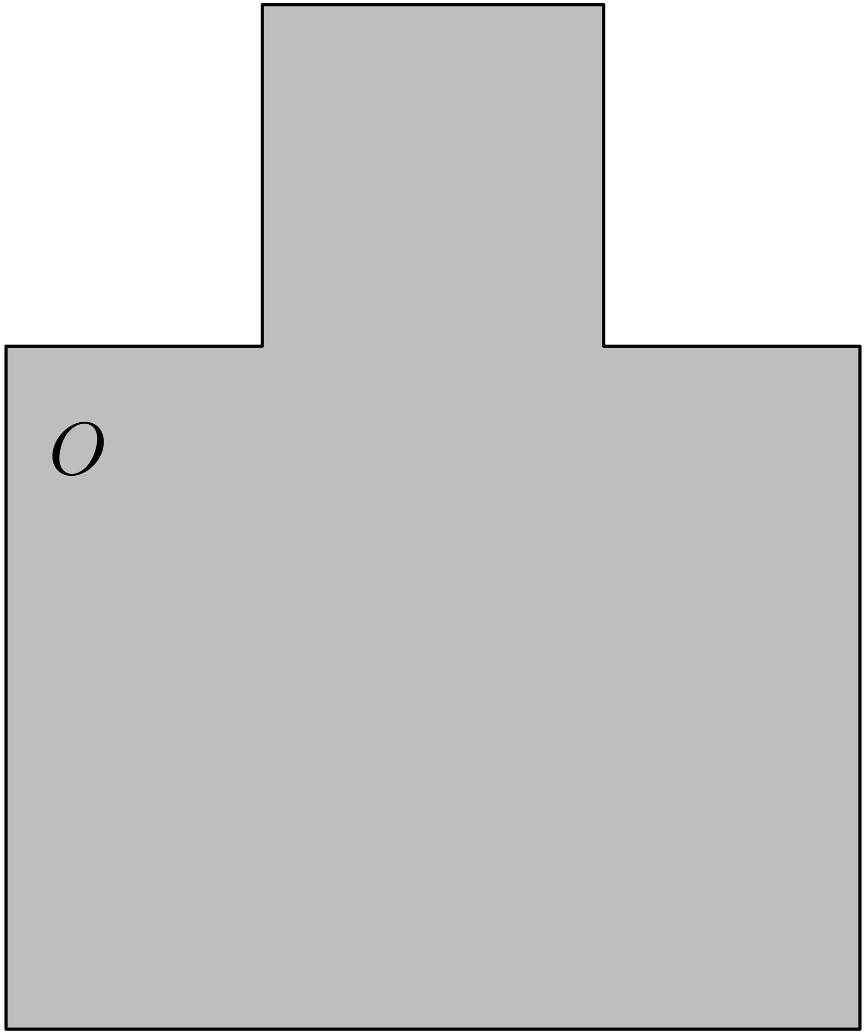
- Starting from O, compute O' as $\quad O'_{|z} \leftarrow O_{|z}^{\uparrow 2\text{mm}}$
- Compute $\textsc{SimpleEnclosure}(O')$





Large cavities

Cavity = enclosure that fits inside the object O



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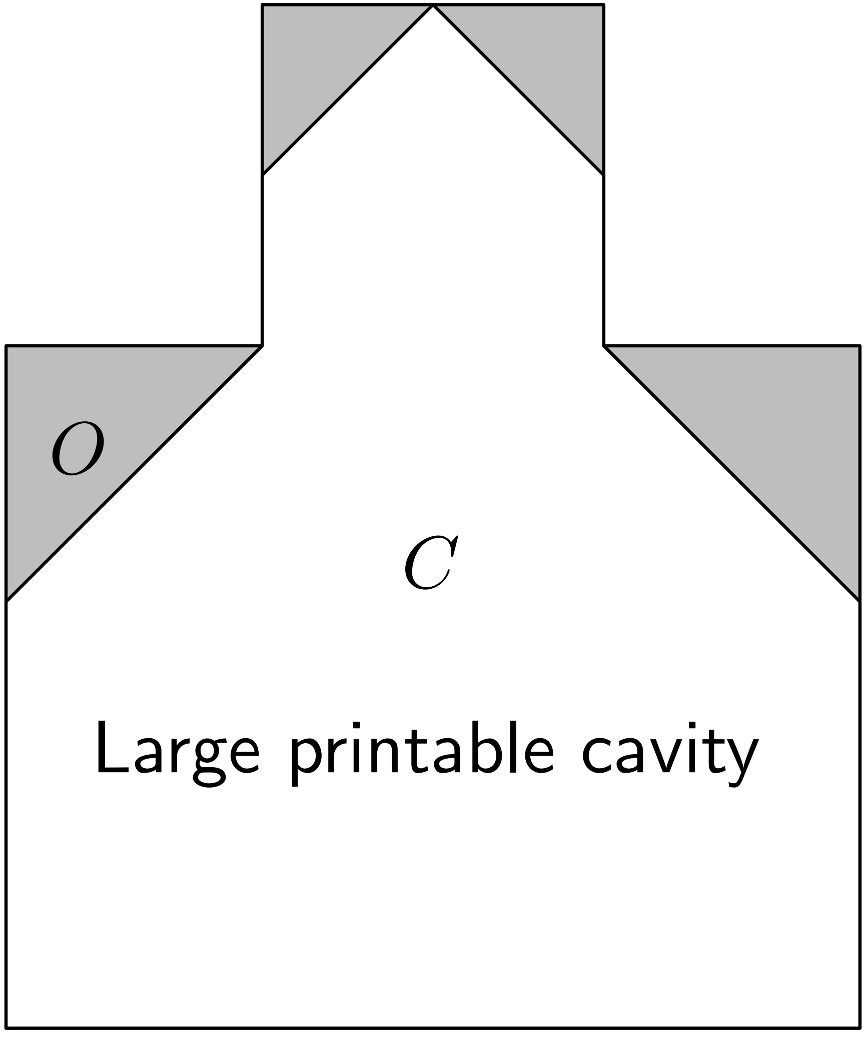
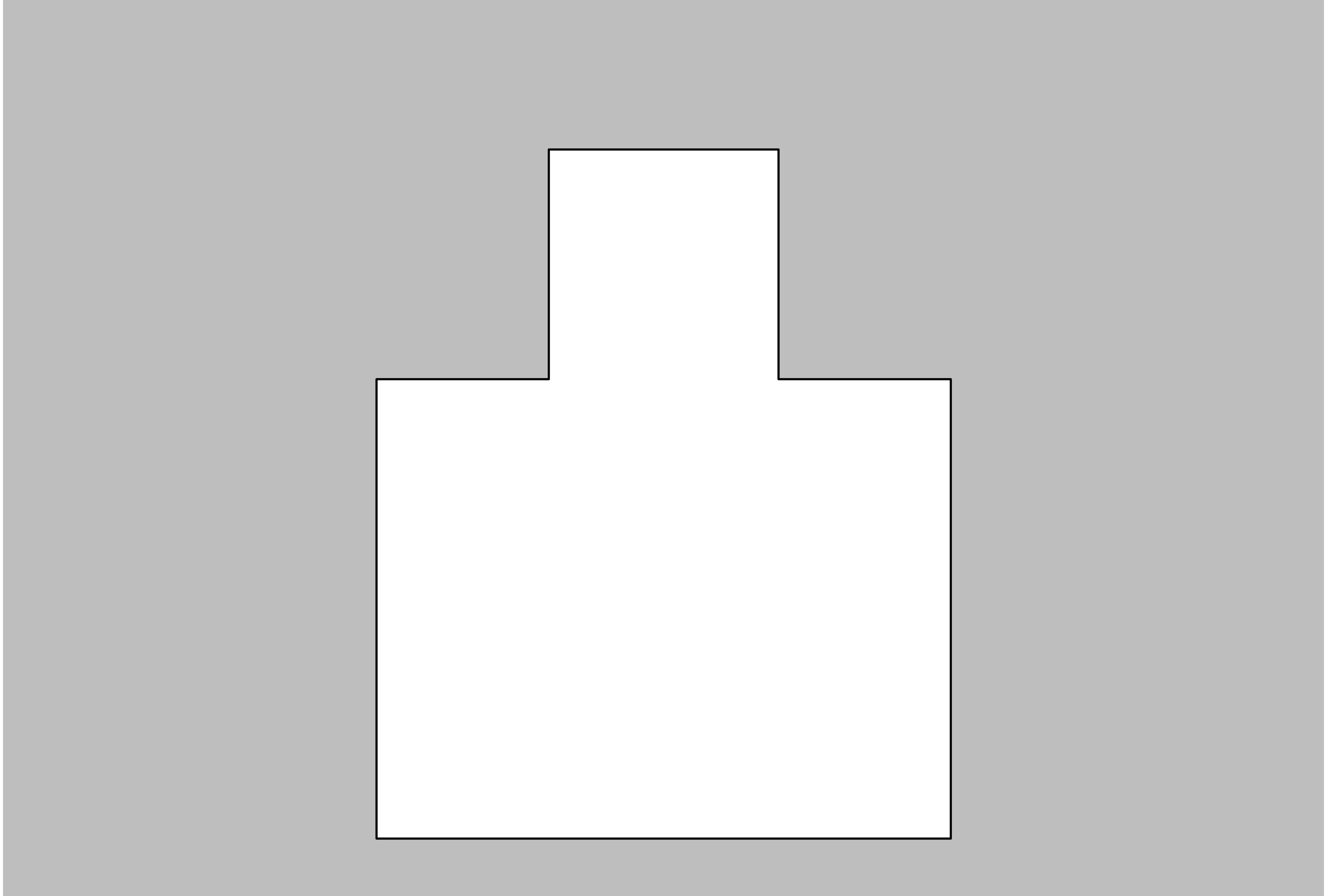


Large cavities

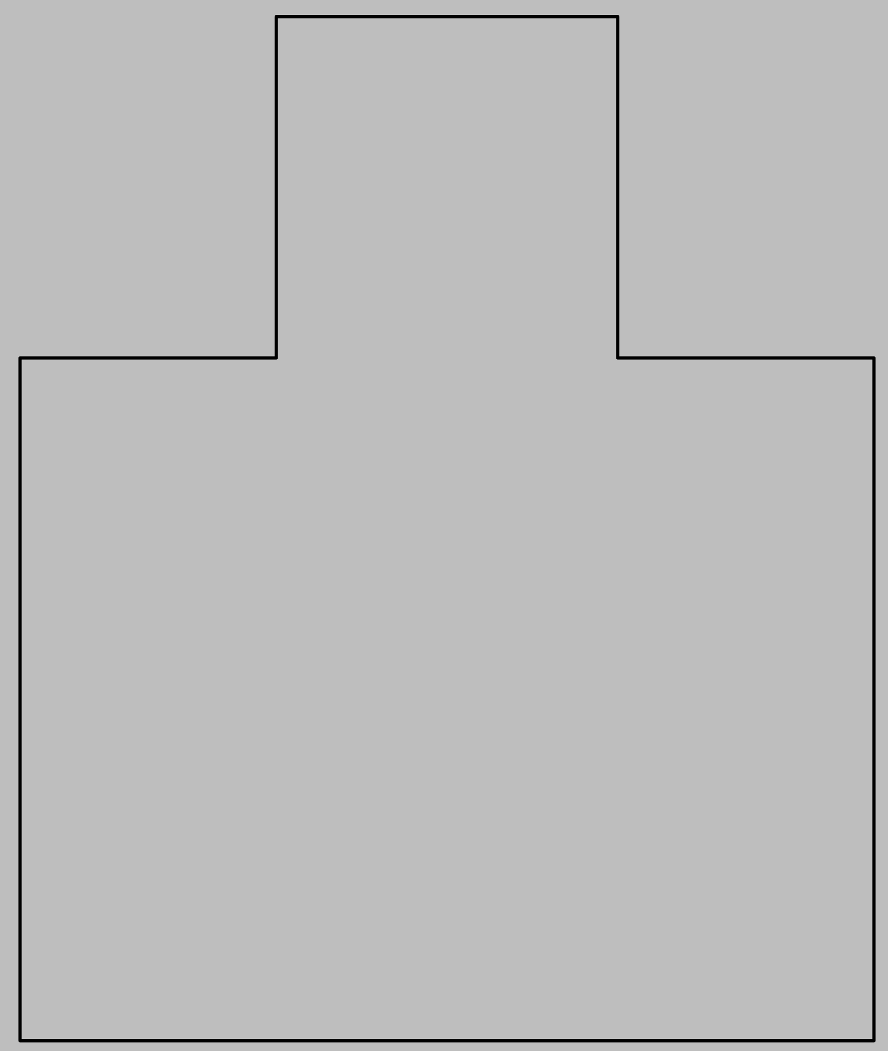
Idea: Use $\textsc{PropagateDown}()$ on the complement of O



Large cavities

Idea: Use PropagateDown() on the complement of O

But this completely fills the object...



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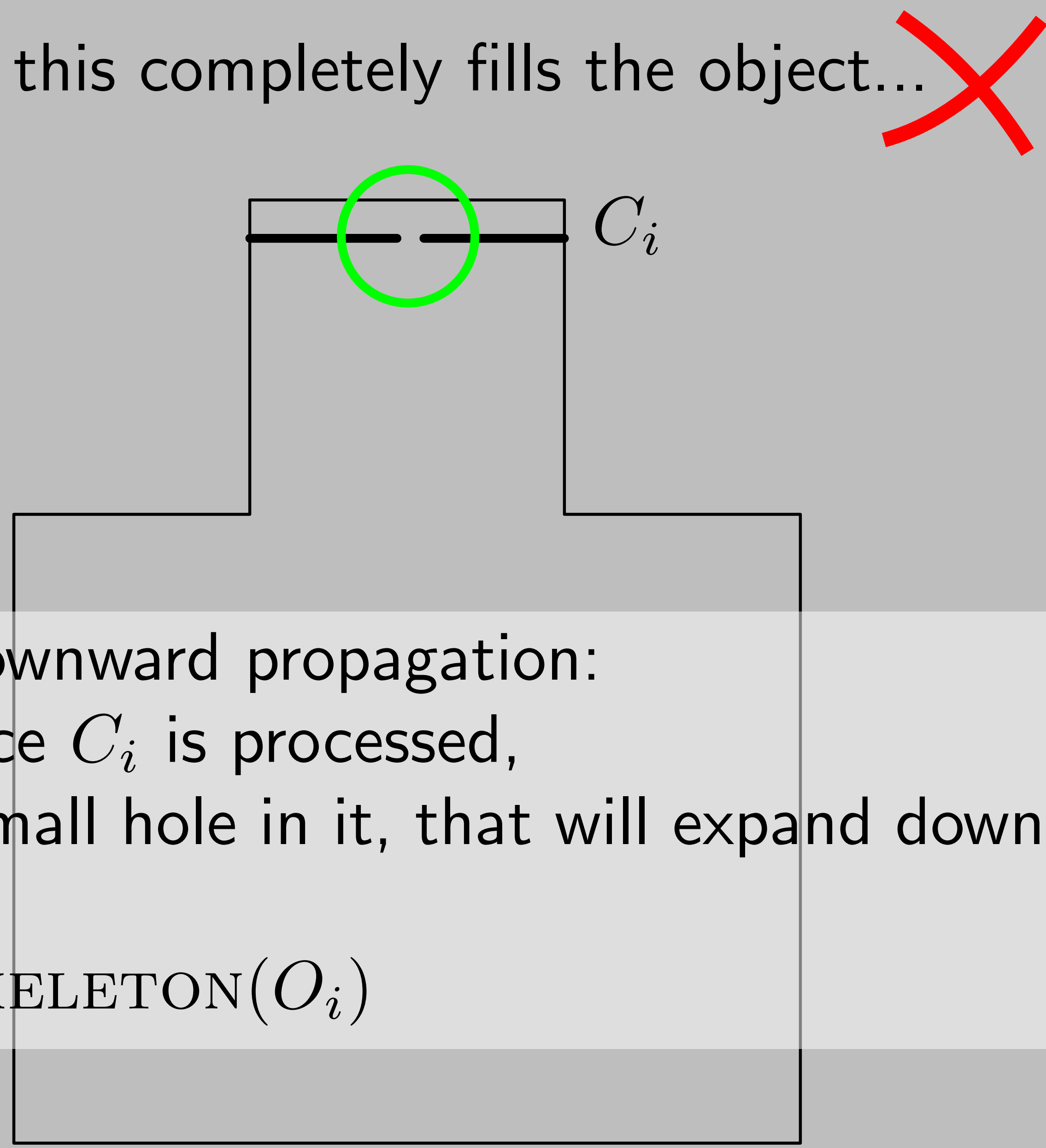
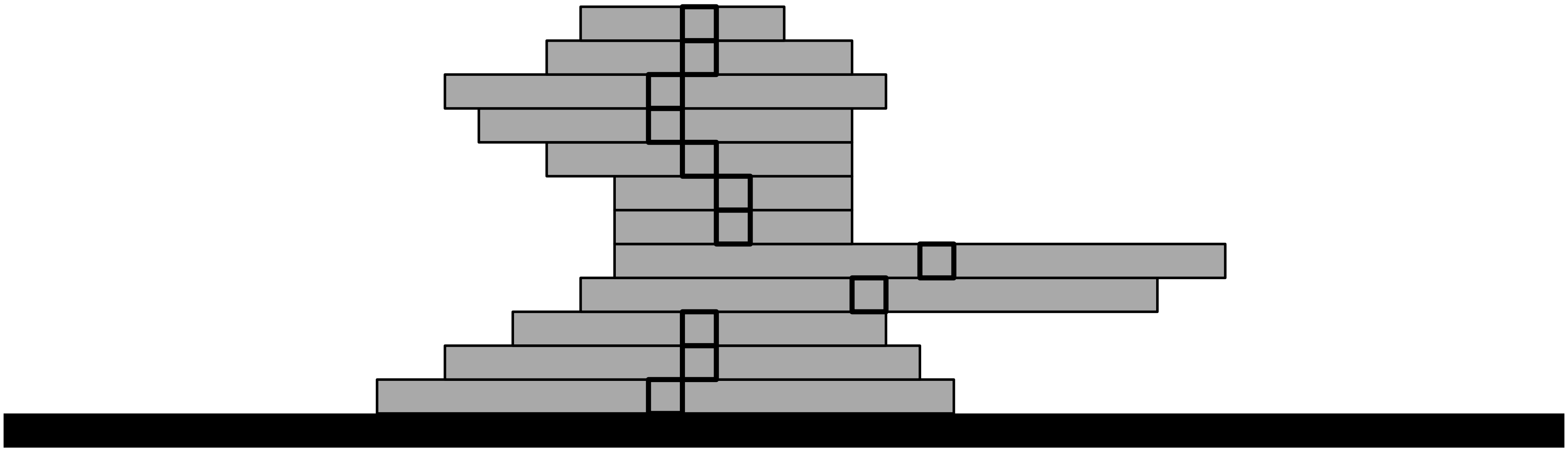


During the downward propagation:
After each slice C_i is processed,
we punch a small hole in it, that will expand downwards (via erosion):
$C_i \leftarrow C_i \setminus \textsc{Skeleton}(O_i)$

Cavities in the discrete setting



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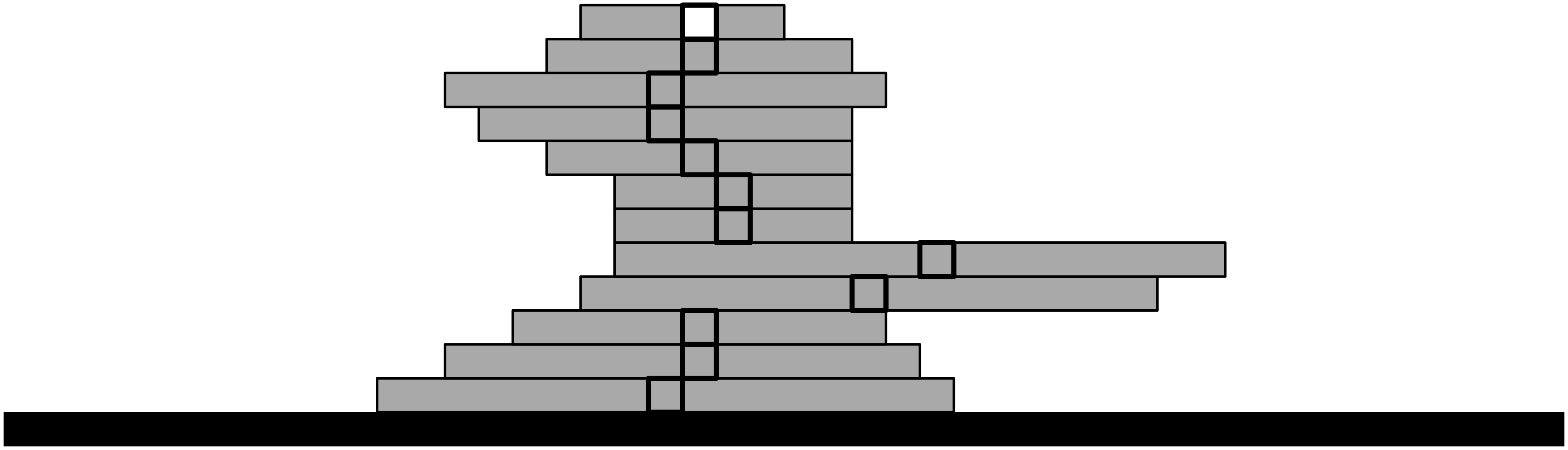

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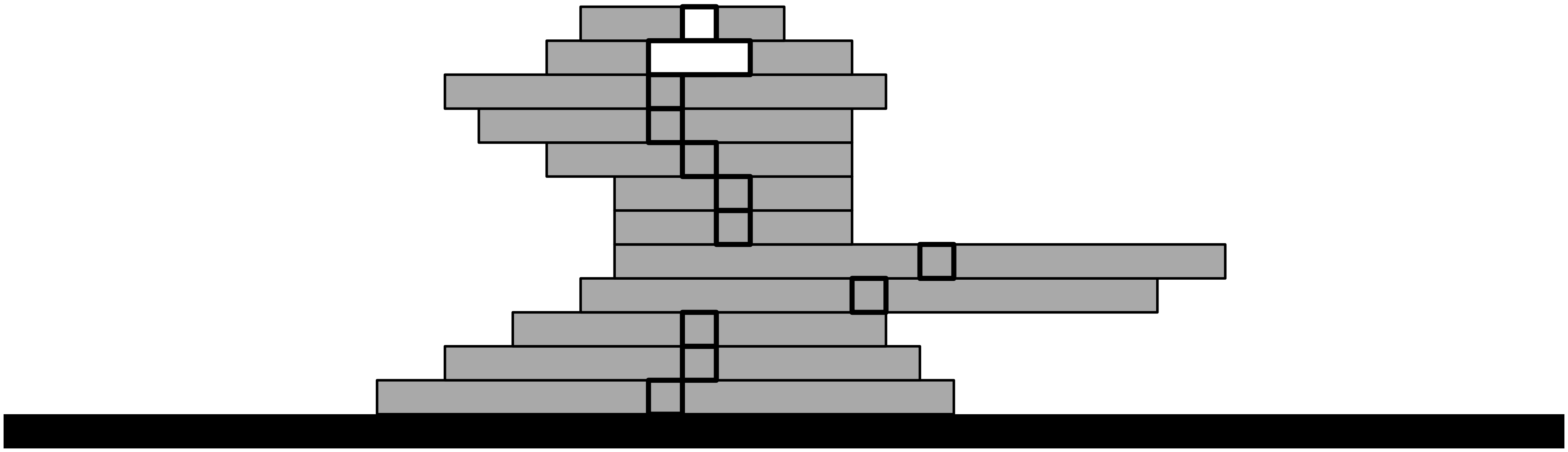

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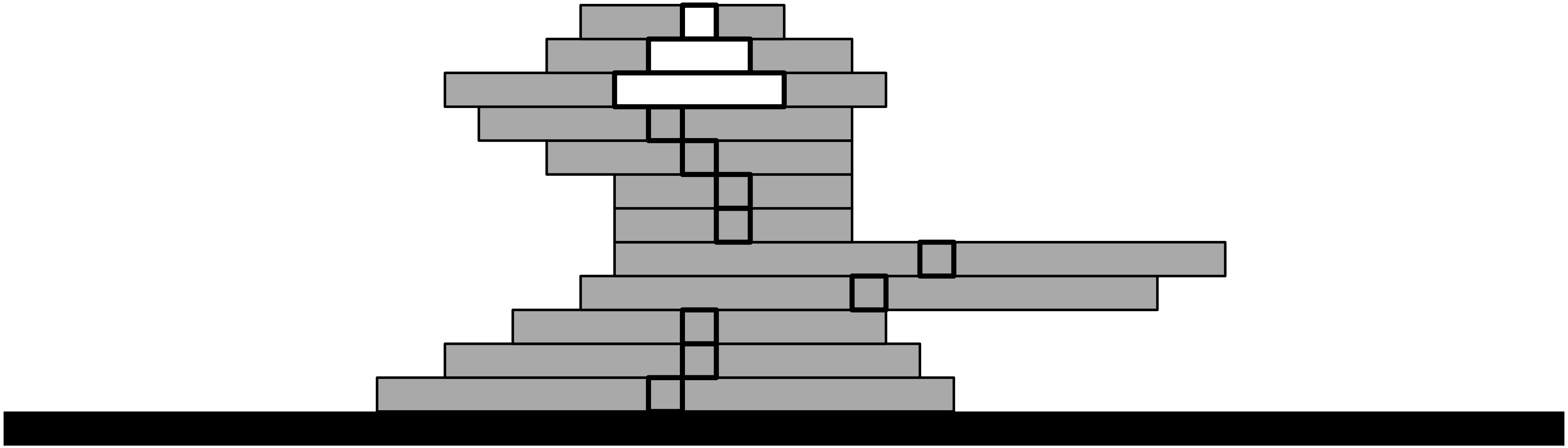

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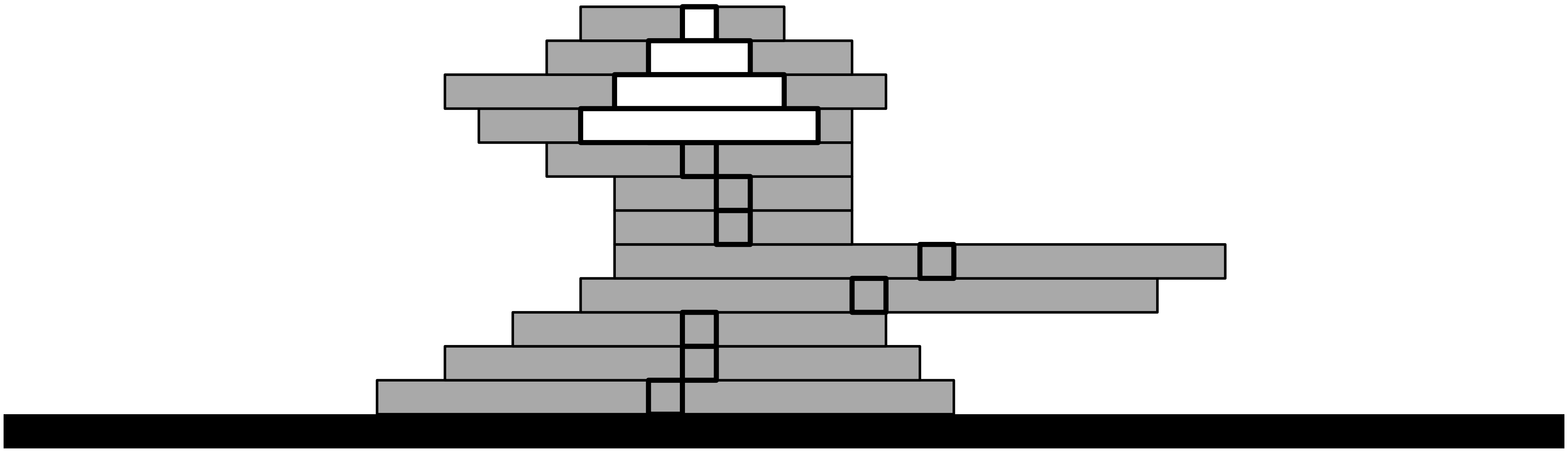
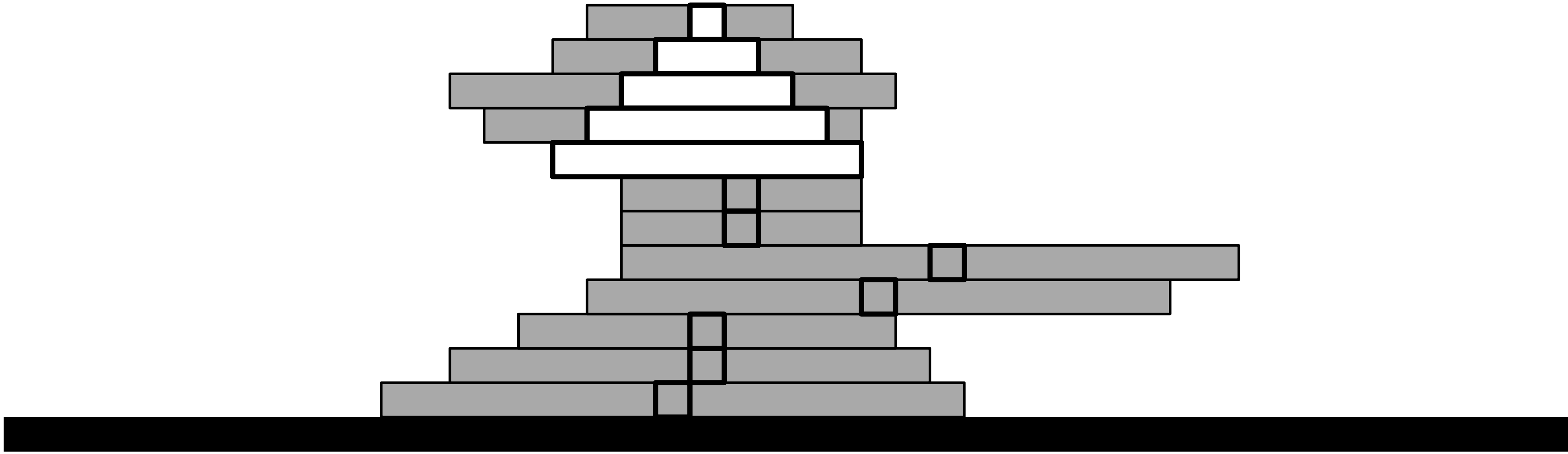
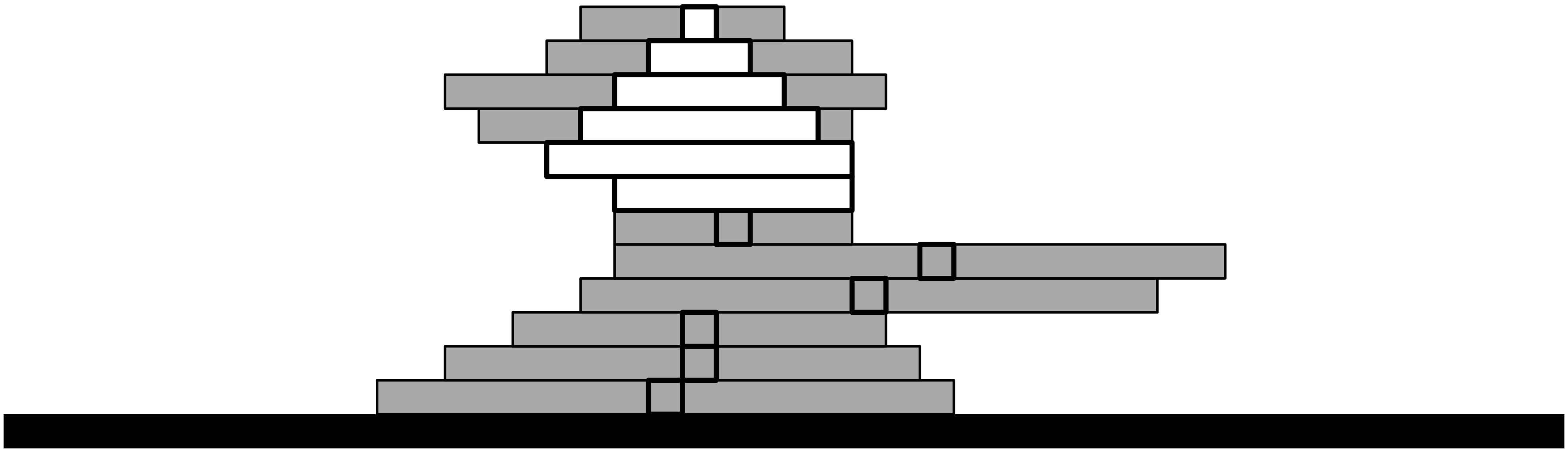


Cavities in the discrete setting



Cavities in the discrete setting



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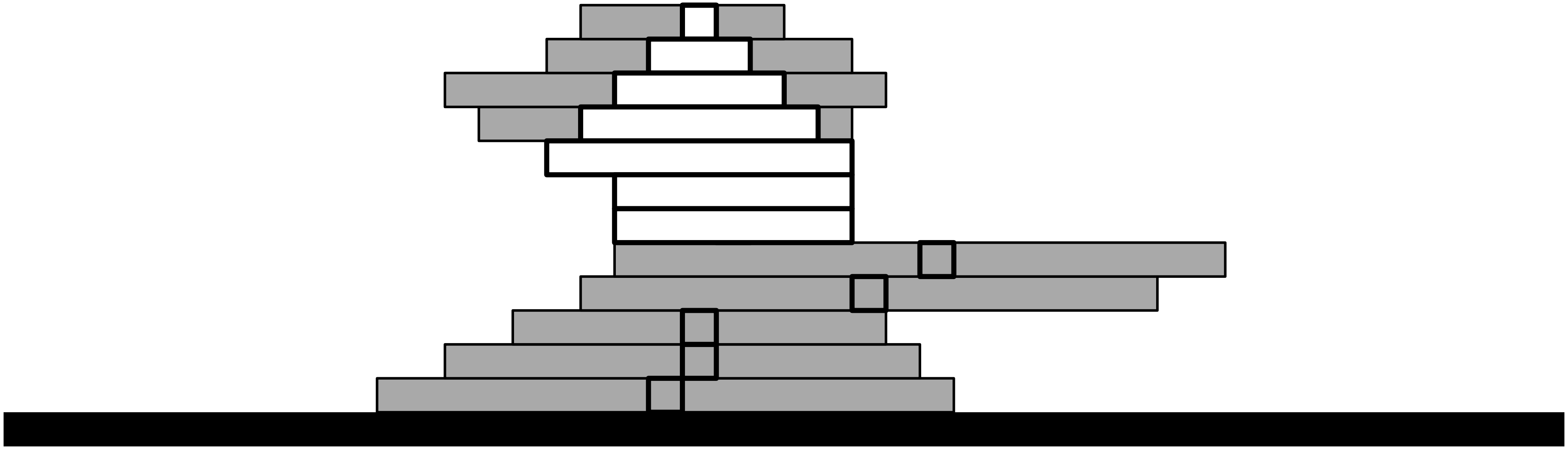

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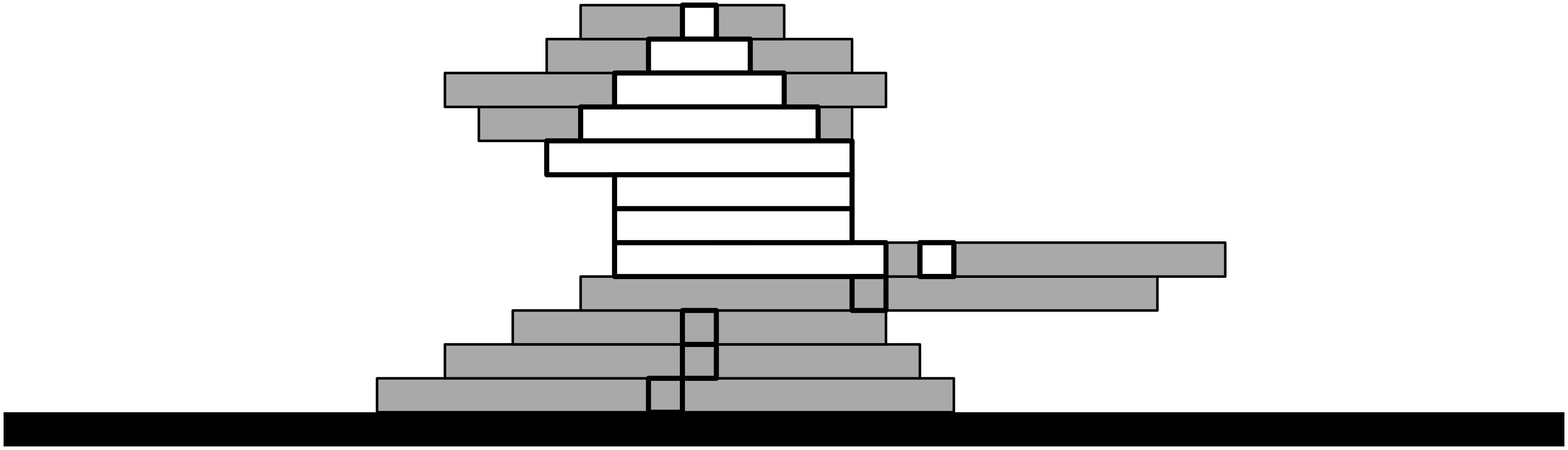

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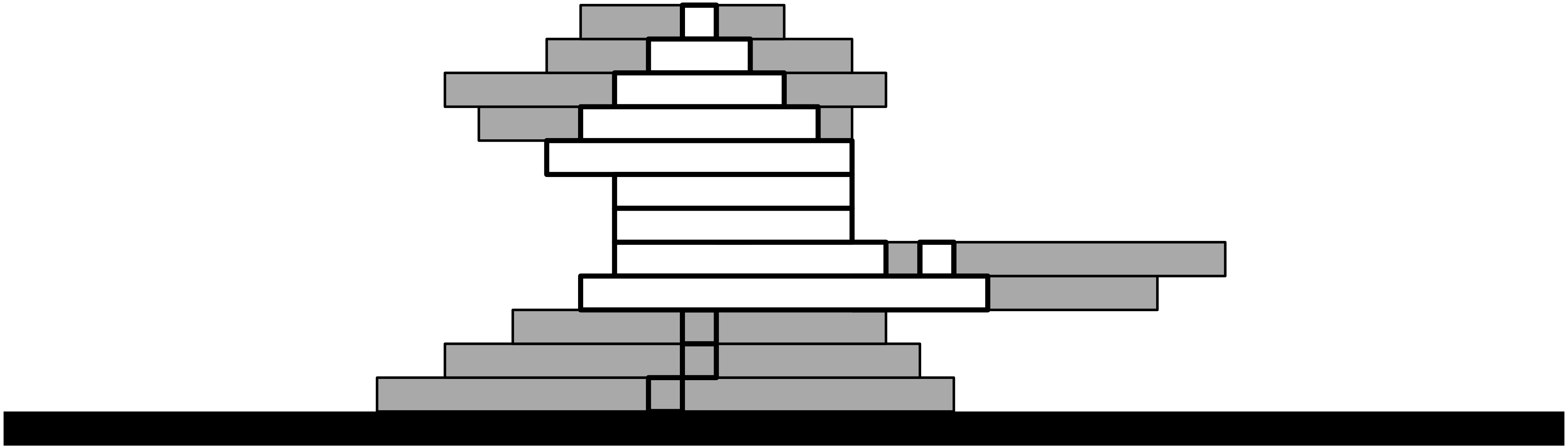
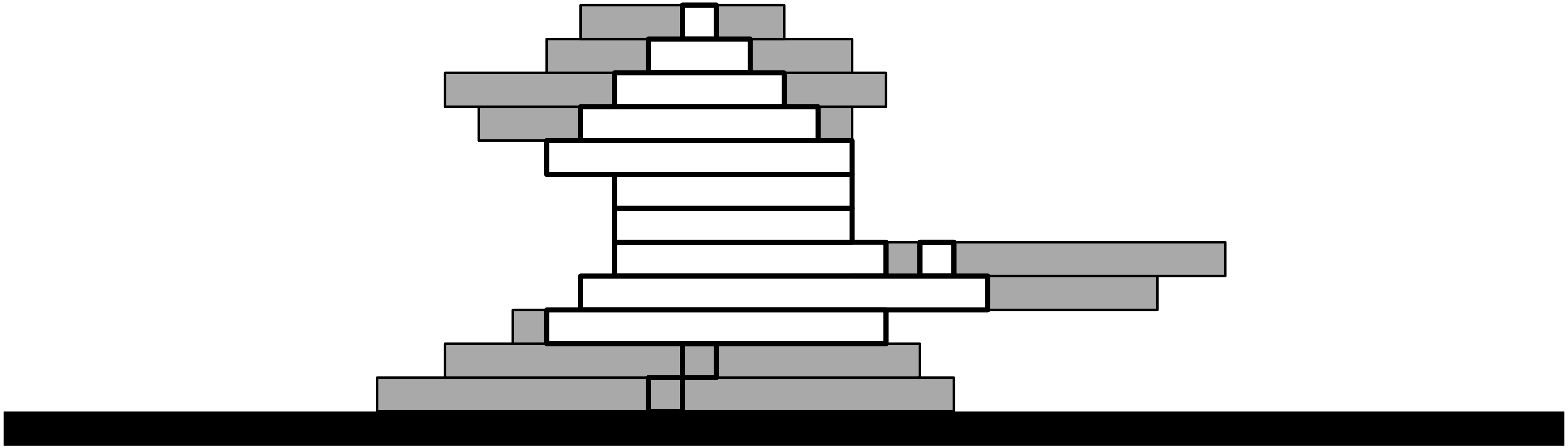
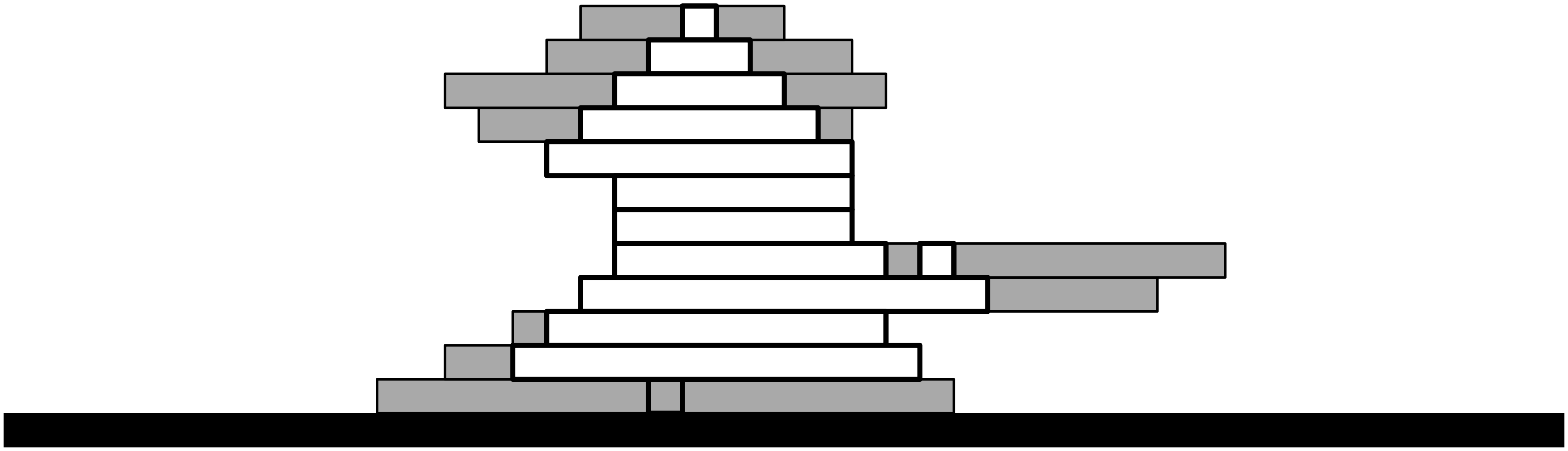


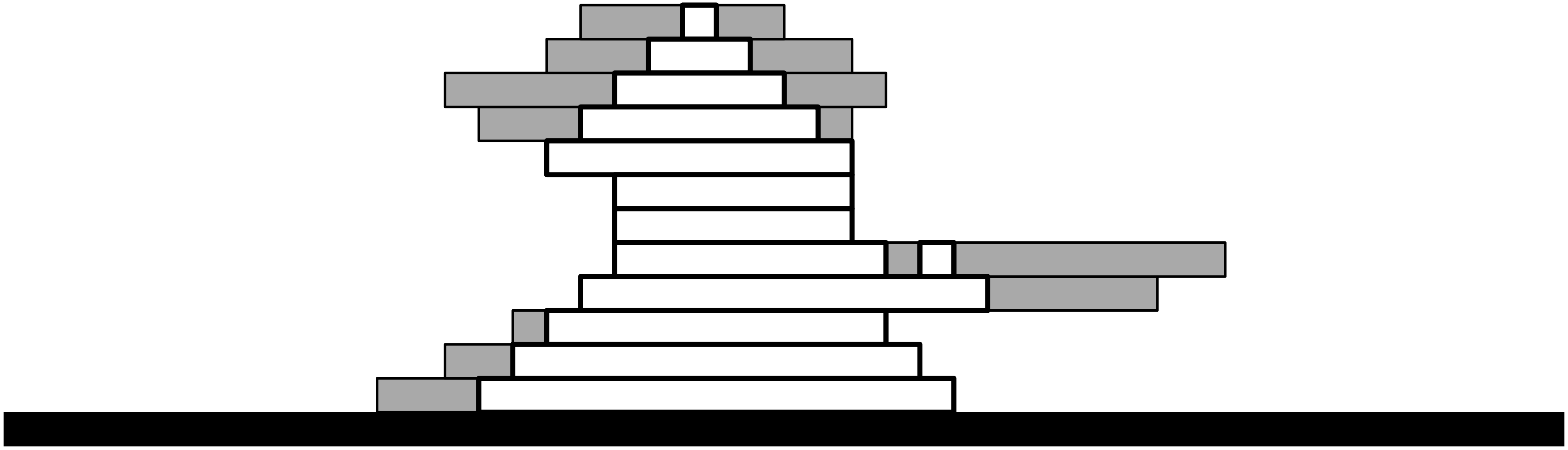
Cavities in the discrete setting



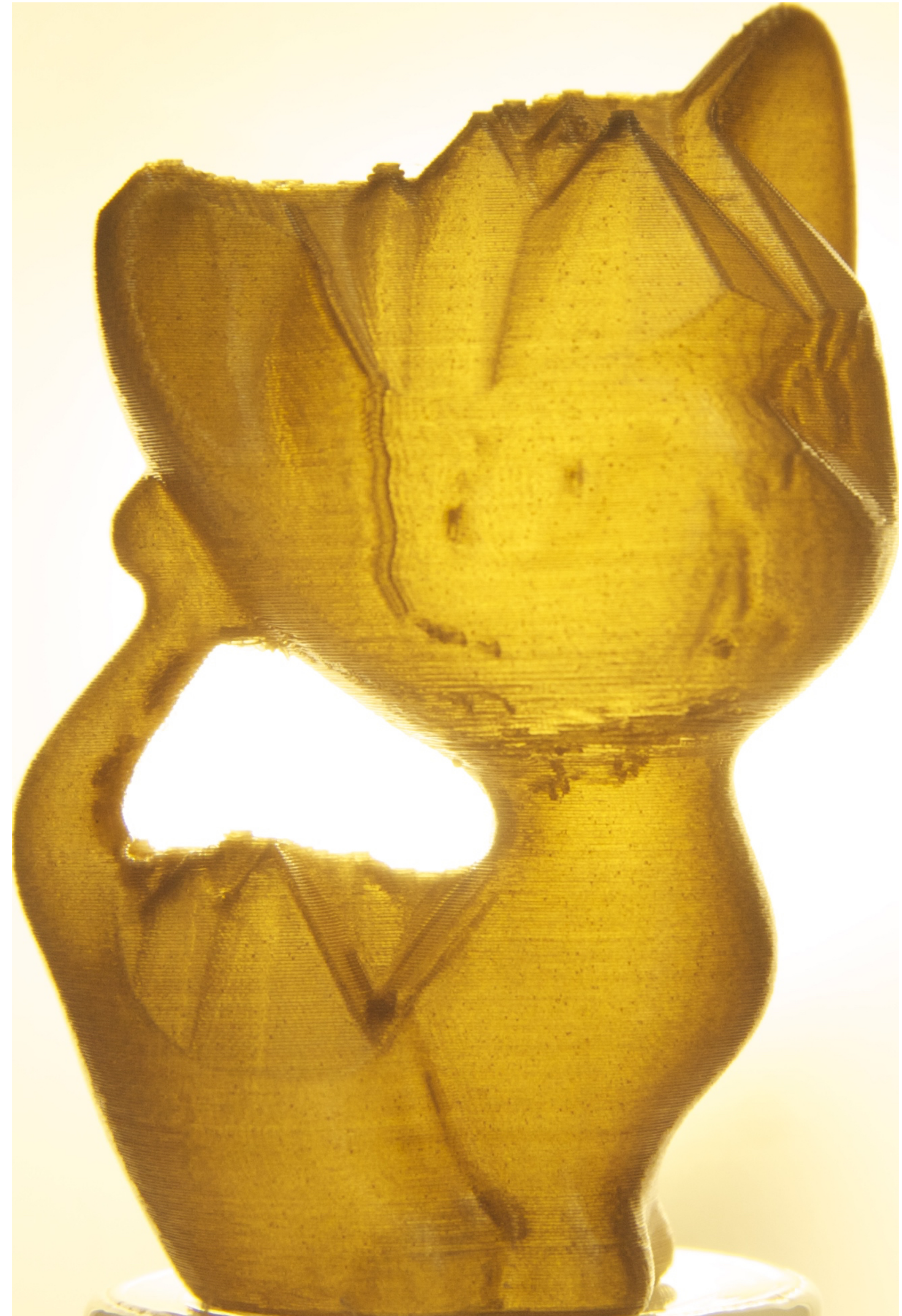
Cavities in the discrete setting



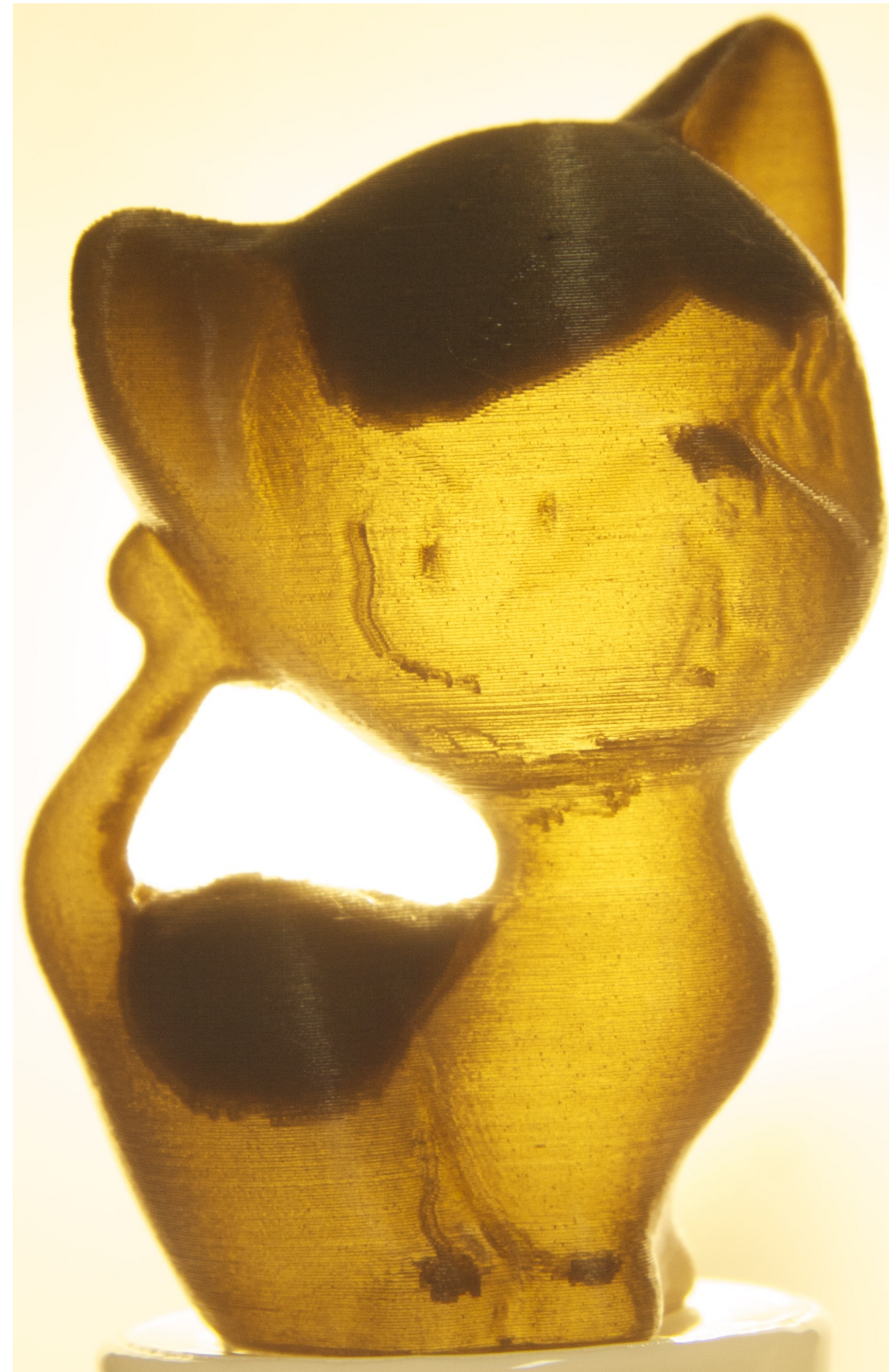
Cavities in the discrete setting



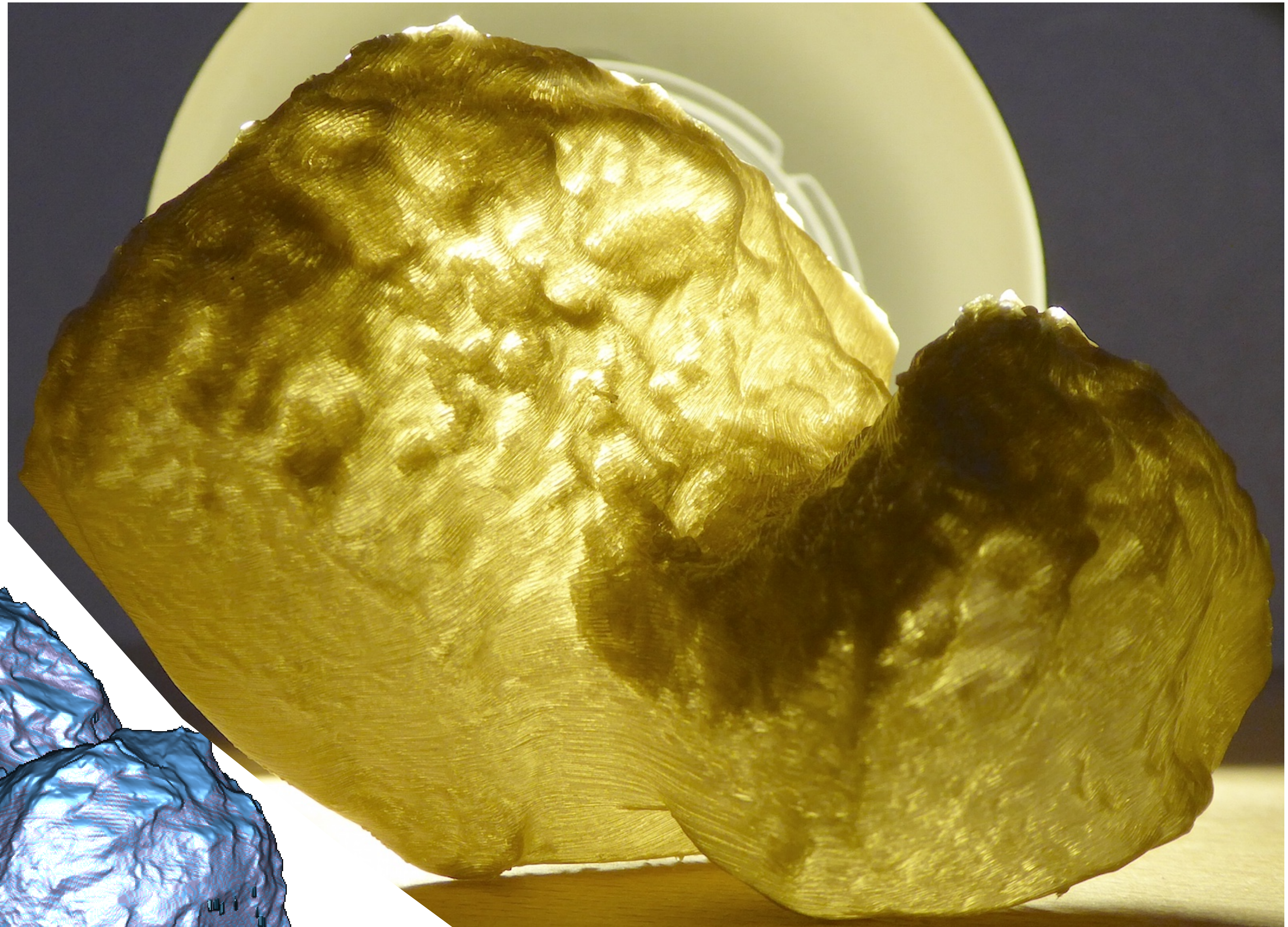
Cavities: results

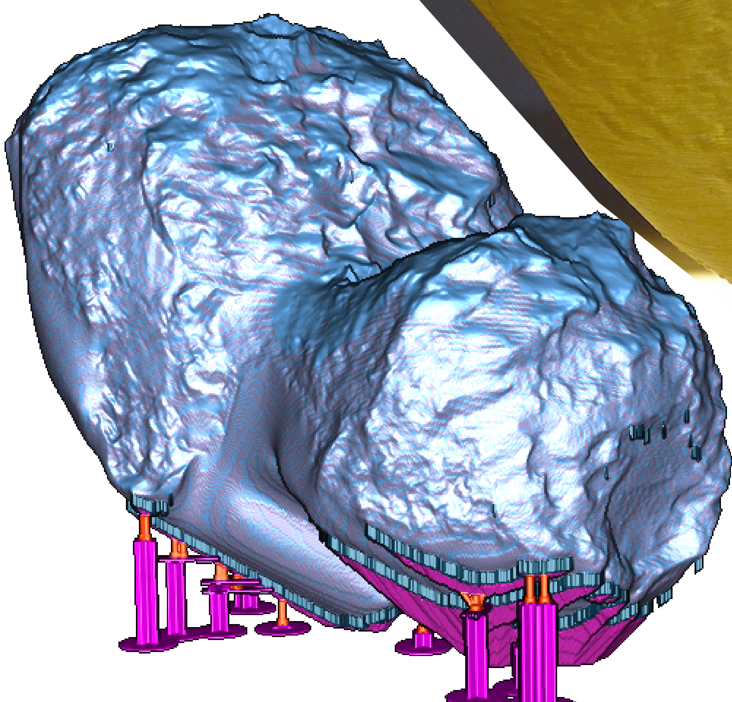


Cavities: results

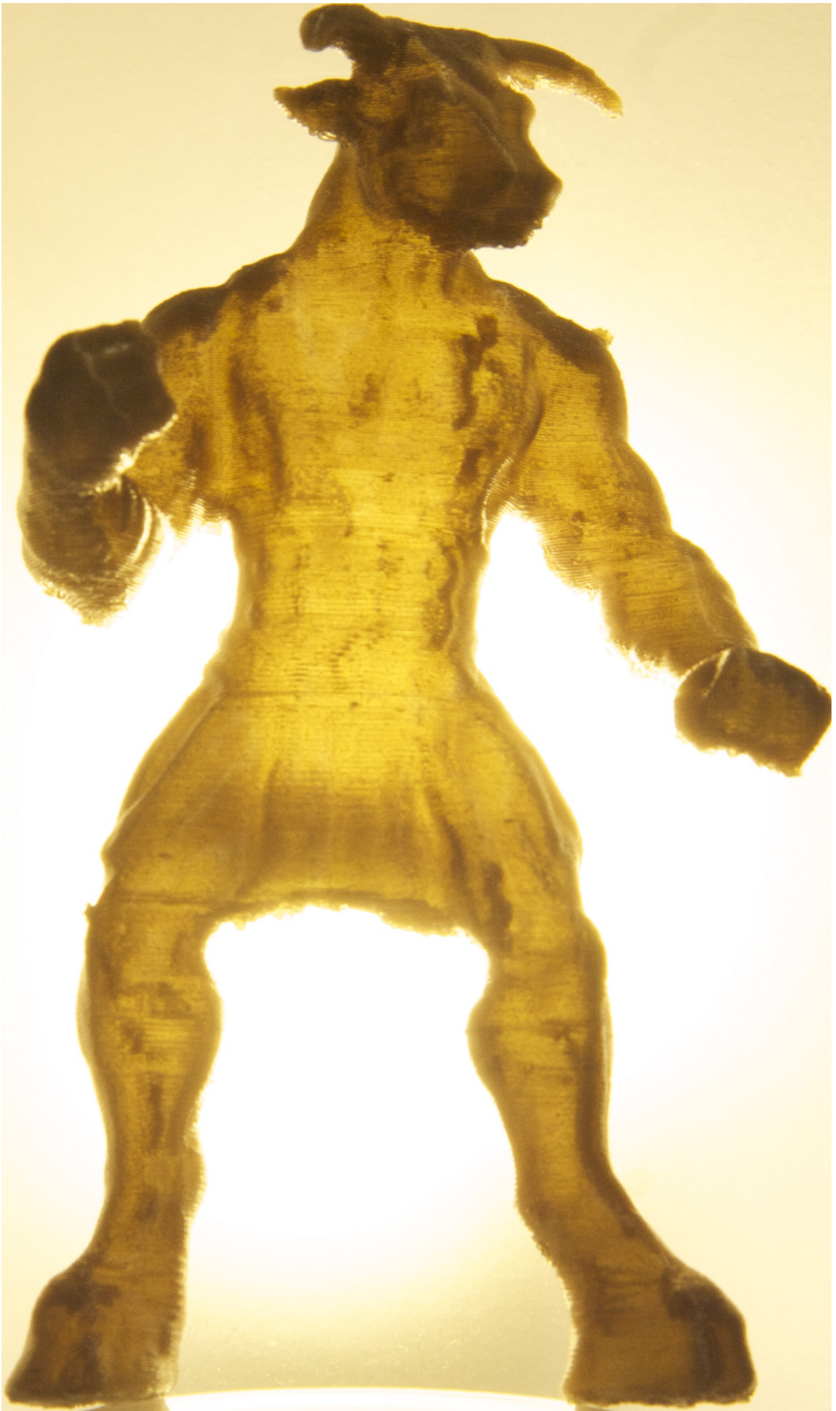


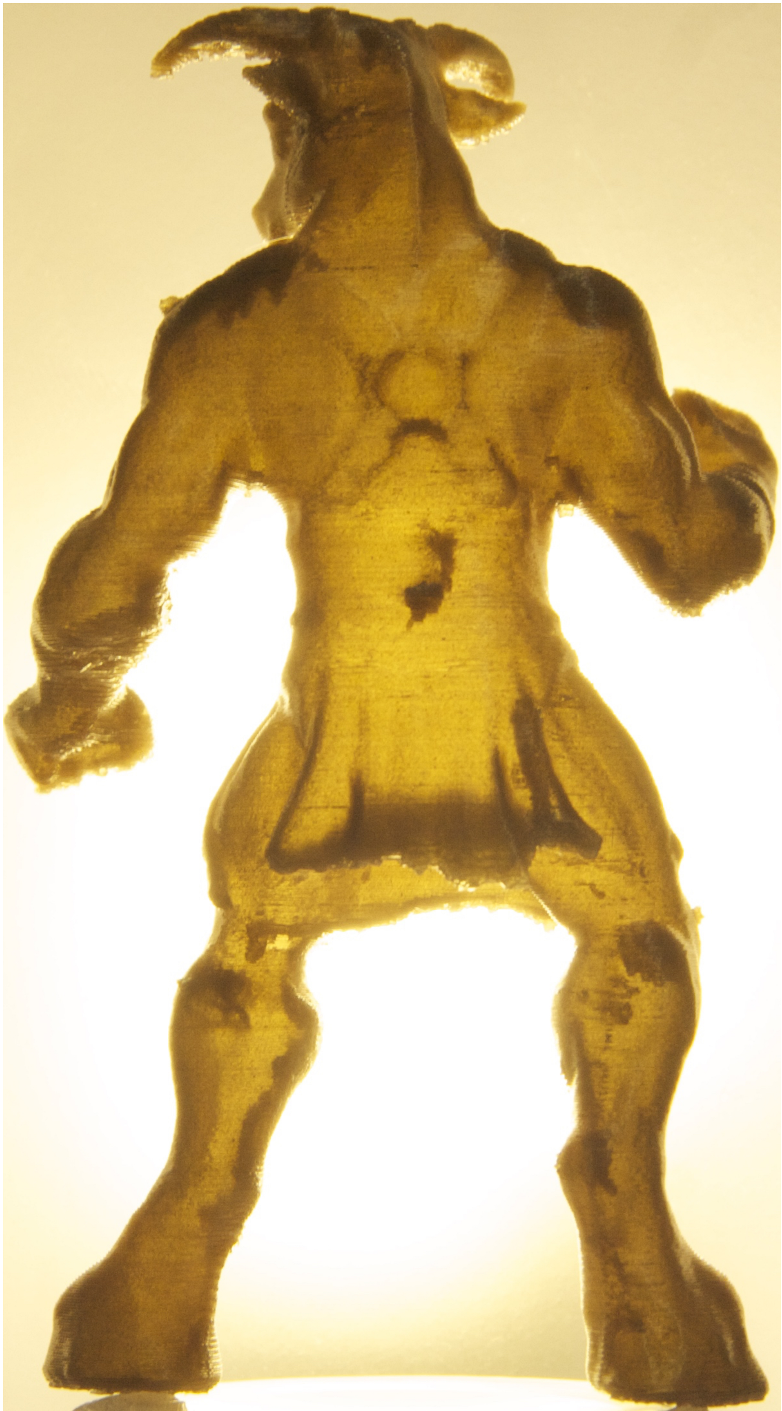
Cavities: results





Cavities: results





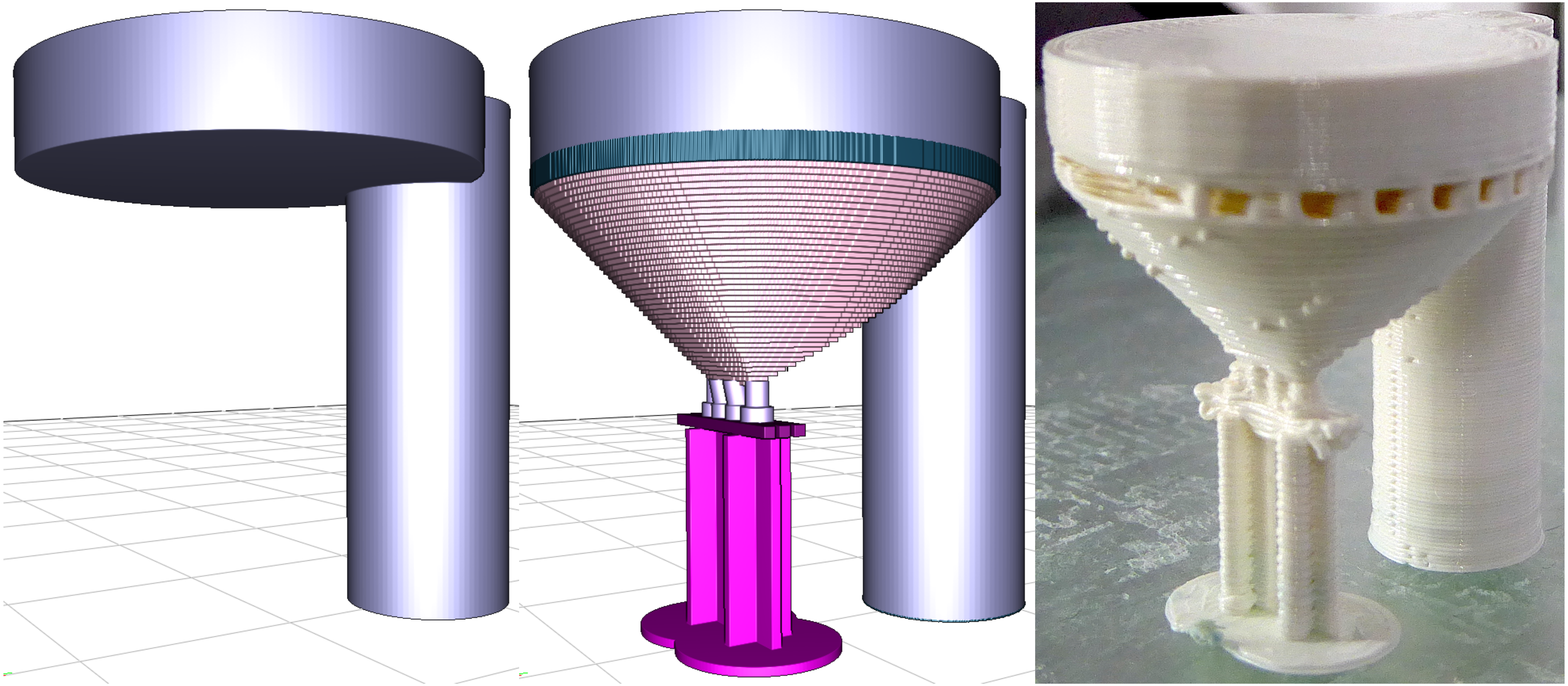
Cavities: results

	This paper		State of the art	
Object	**Hollow**	**Hollow w/ support**	**Infill**	**Infill w/ bridges**
Comet 67P	1329 (56’53”)	1453 (63’18”)	4238 (152’41”)	4328 (156’51”)
Minotaur	1186 (50’30”)	1576 (72’31”)	2267 (85’28”)	2713 (107’24”)
Kitten	2151 (87’43”)	—	4309 (153’55”)	—
Bear	998 (46’49”)	1469 (74’25”)	991 (46’36”)	1245 (59’15”)

estimated print time

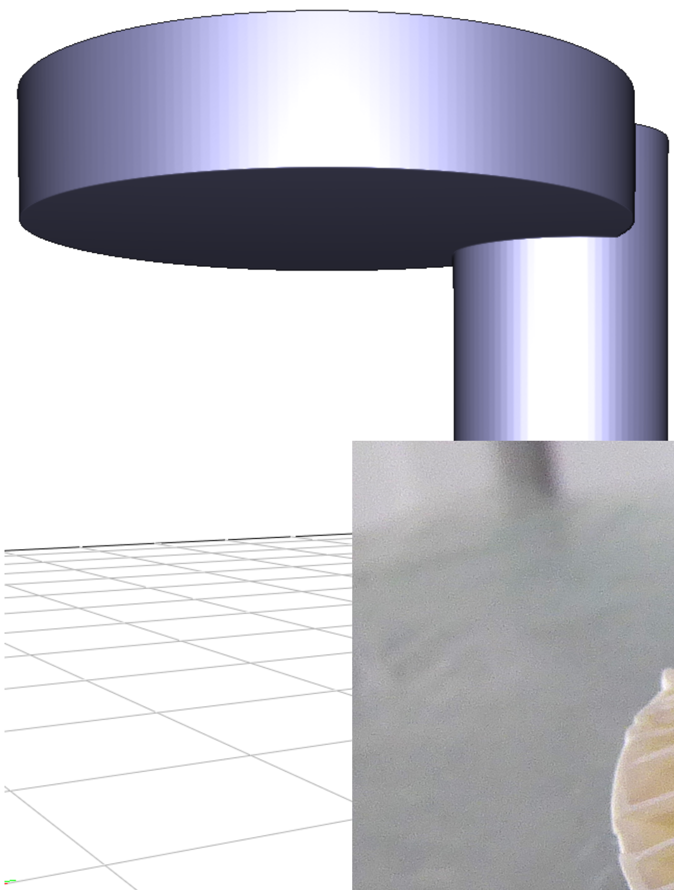
length of filament (mm)

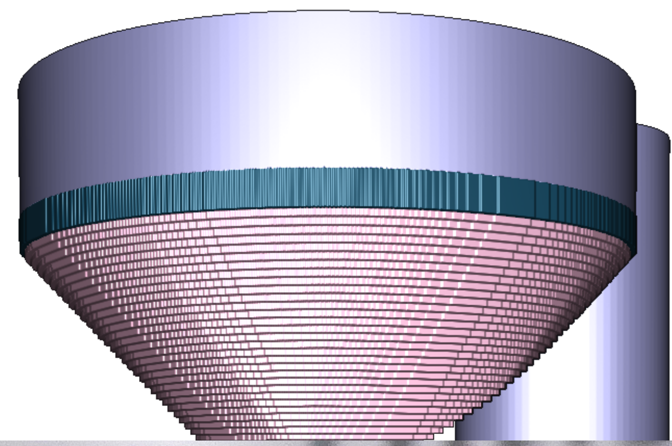
Low complexity scaffolding

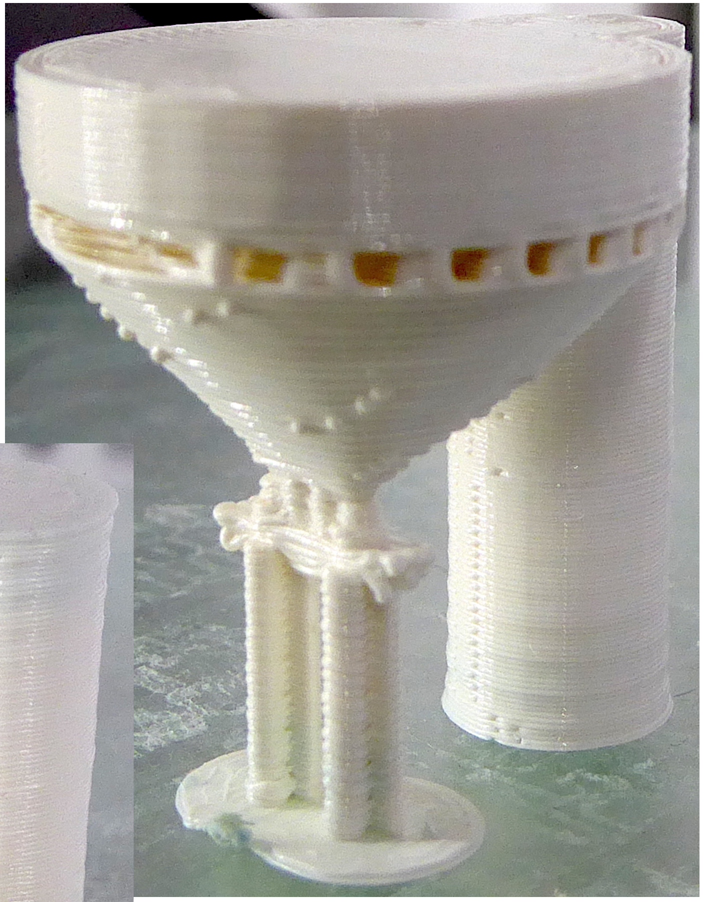


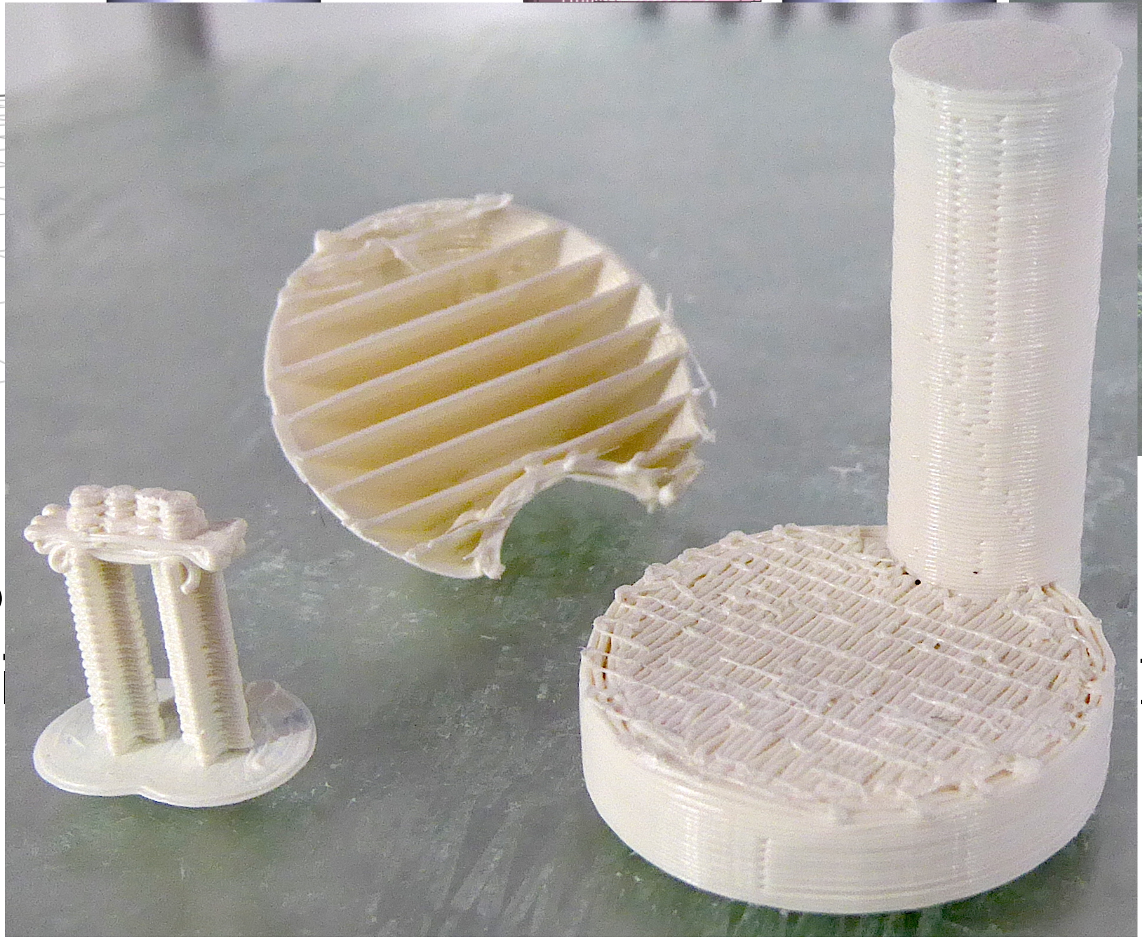
- Support $= \textsc{PropagateDown}(O) \backslash O$
- Add pillars for local minima [Dumas *et al.*'14]

Low complexity scaffolding



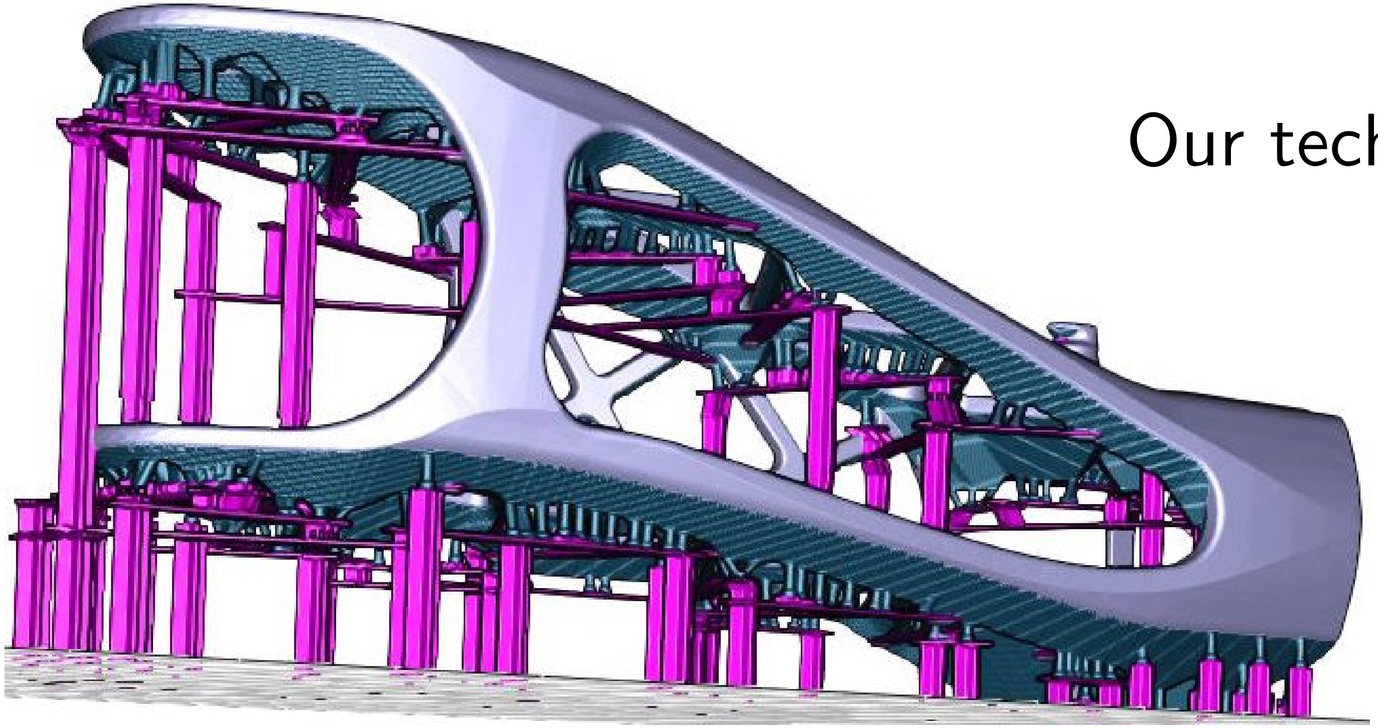






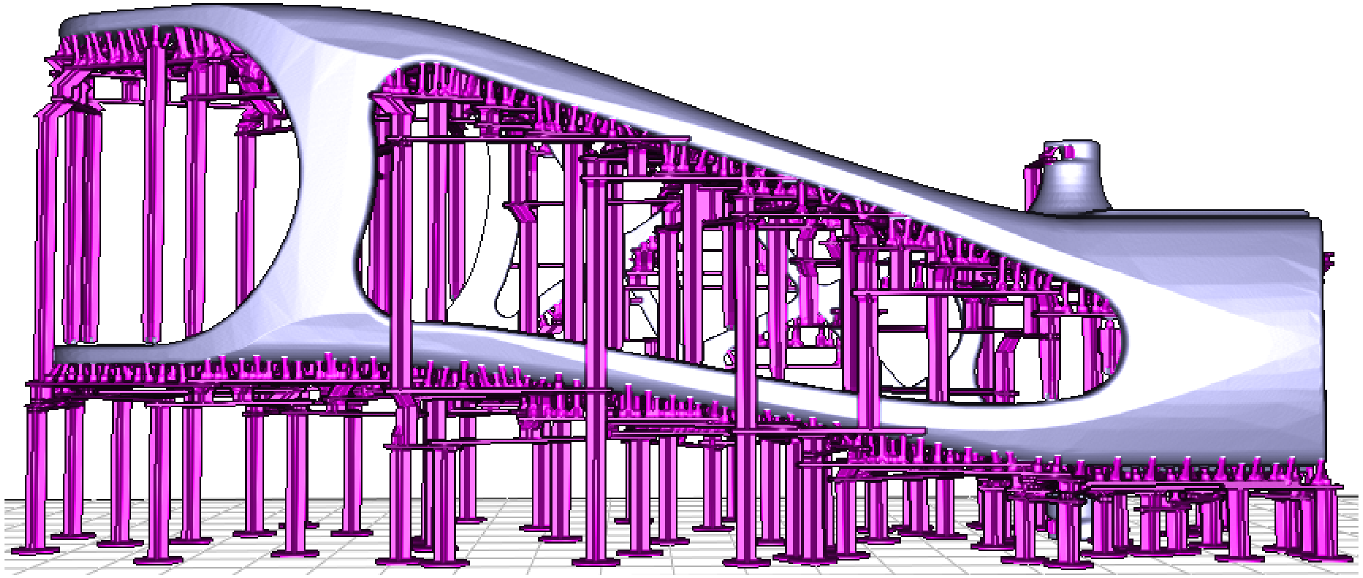
- Suppo
- Add pi 14]

Low complexity scaffolding



Our technique

Dumas *et al.*
[SIGGRAPH'14]



Protective wall

Protective wall

- Using only $\textsc{PropagateDown}(O')$ $\Rightarrow$ Easy separation