[1-3]

CLIMATE ATTRIBUTION SCIENCE:

CAN WE DETERMINE WHICH EXTREME WEATHER EVENTS ARE 'CAUSED' BY GLOBAL WARMING?

28.11.2019
Peter Lippmann
Seminar: How do I lie with statistics?
Supervision: Prof. Dr. Ullrich Köthe

WEATHER – NOW MORE EXTREME THAN EVER?

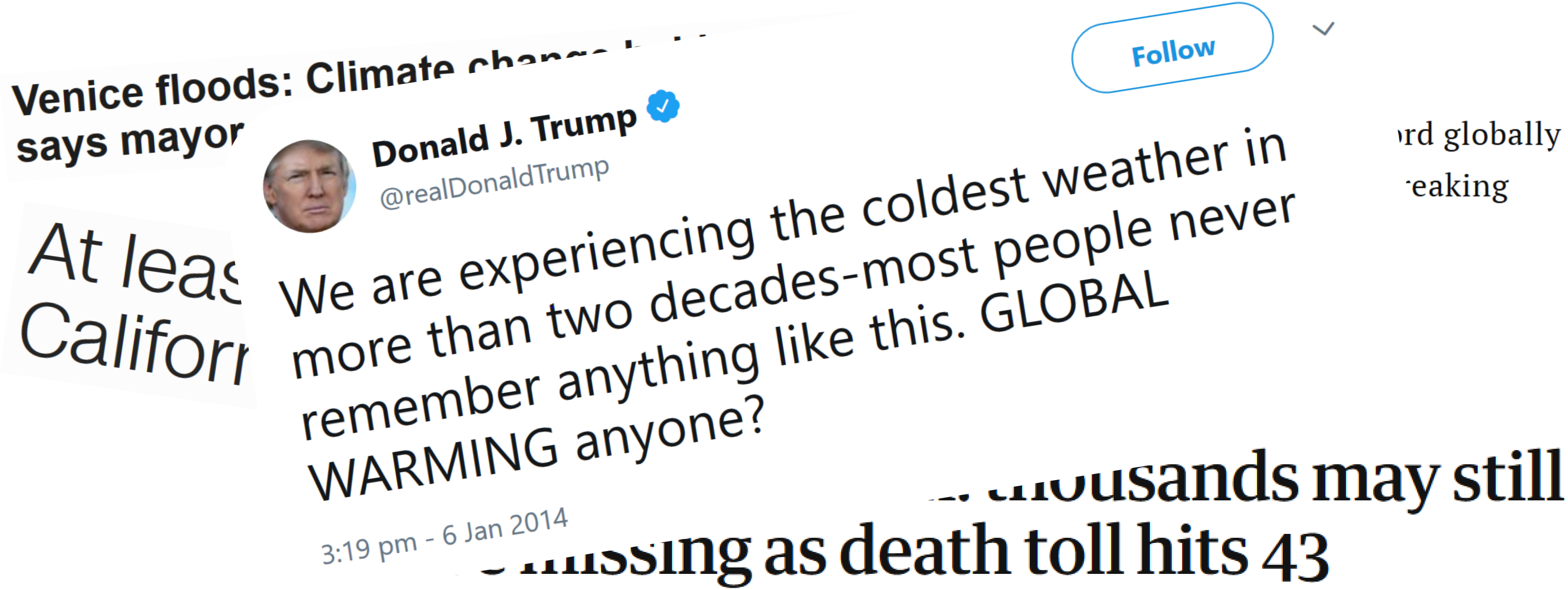
Venice floods: Climate change behind highest tide in 50 years, says mayor

July 2019 was the hottest July and the hottest month on record globally since temperature records began in a year of many record-breaking temperatures as heat waves hit many parts of the world.

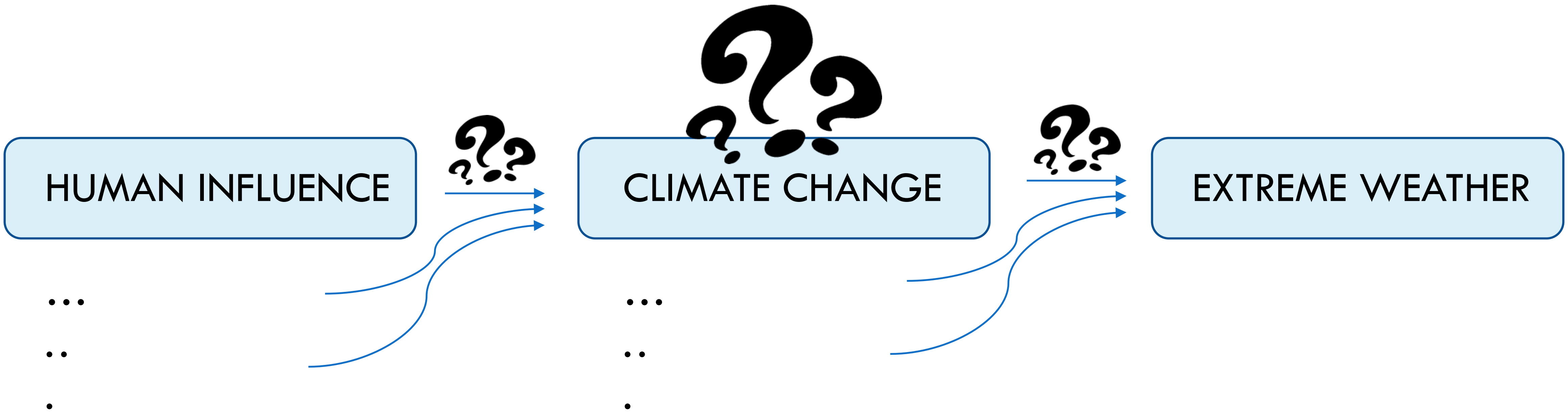
At least 13 wildfires are burning in California

Hurricane Dorian: thousands may still be missing as death toll hits 43

WEATHER – NOW MORE EXTREME THAN EVER?



THE ROLE OF CLIMATE CHANGE



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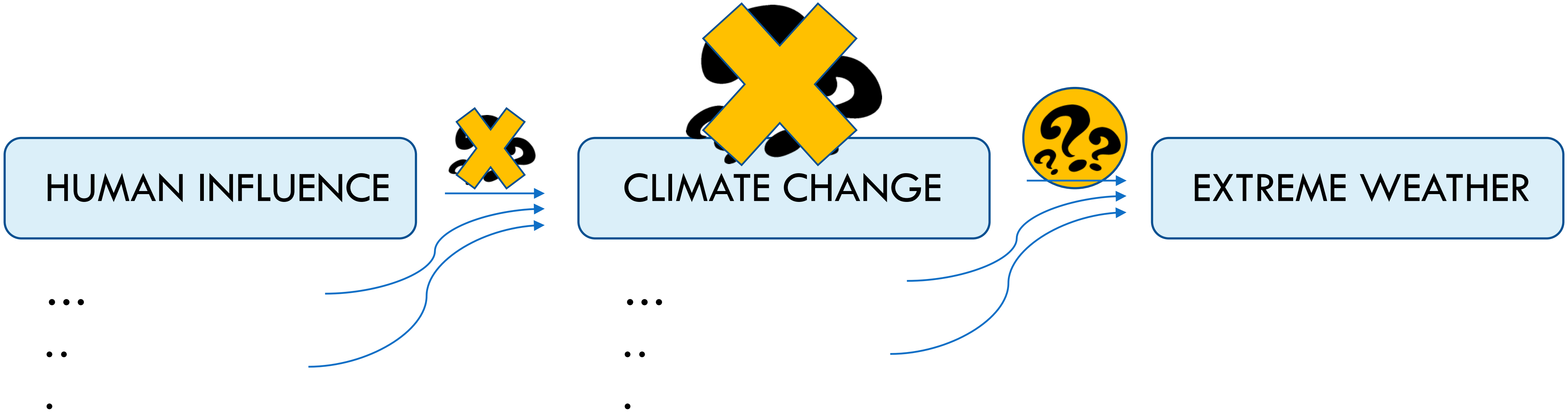


OVERVIEW

1) **What is climate attribution science?**
2) Weather as complex phenomenon
3) How is it done in practice?
4) Conclusion and Outlook

ASKING THE RIGHT QUESTIONS

"Was this extreme weather event caused by climate change? – Yes or No ?"

BUT: WEATHER IS A **MULTICAUSAL and COMPLEX** PHENOMENON!

Better questions:

- Did (anthropogenic) climate change make an extreme weather event **more likely**?
- Did it make it **more severe**?
- And if so, how much?

CLIMATE ATTRIBUTION SCIENCE

WHAT ARE EXTREME WEATHER EVENTS?

- Extreme Cold
- Heat waves
- Droughts
- Precipitation
- Storms
- …

Wildfires

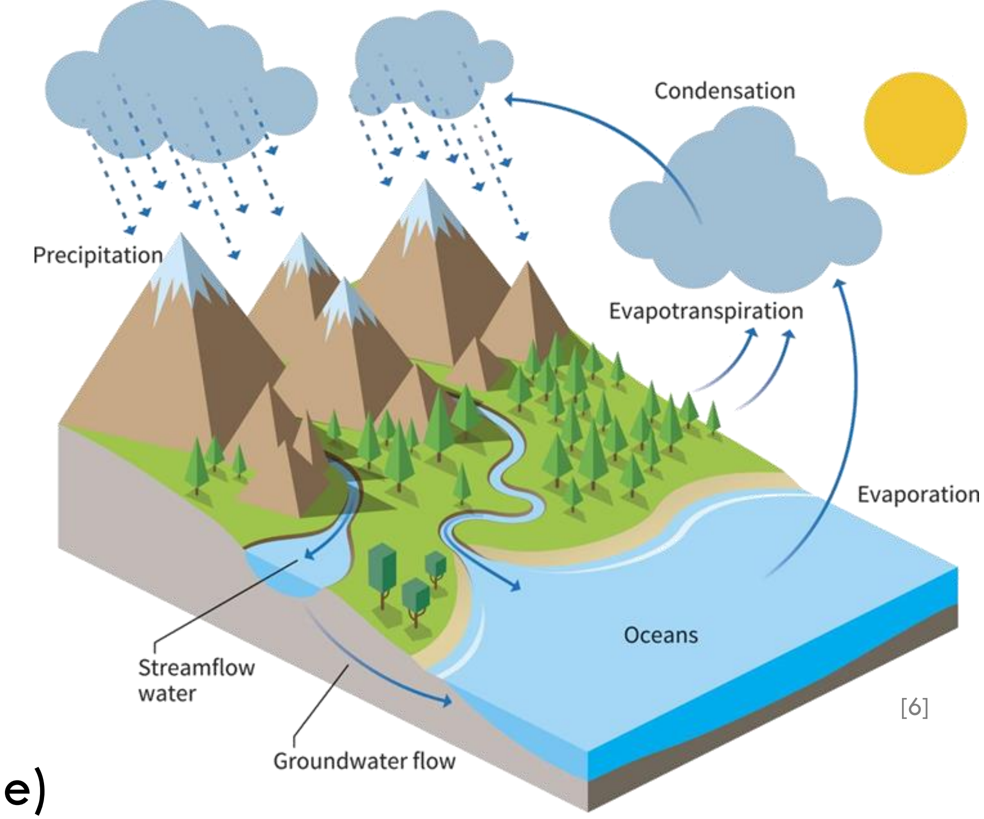
Floods

[4]

[5]

WHAT DOES IT RELY ON?

1. Sound physics:



CLIMATE

- thermodynamical trends
  - global mean temperature
  - water vapour in the atmosphere
  - sea level

WEATHER

- small noisy dynamics
- chaotic (unpredictable)

Robust predictions based on simple physics causations:

✓ Higher temperatures → more evaporation

✓ Warmer atmospheres hold more moisture → heavier rain/snow

✓ Warmer oceans feed more energy into hurricanes

WHAT DOES IT RELY ON?

2. Historical observations:

- How are the frequency and characteristics of extremes changing?
- Problems: - Extreme events are **rare** by definition → very few previous events
  - records exist only for a few decades → new 'extremes' appear frequently

Need to complement each other

3. Computer simulations:

- Necessary since no climate experiments possible
- Require profound **understanding of mechanisms and influences** behind weather extremes

WHAT ARE POSSIBLE OUTCOMES OF ATTRIBUTION STUDIES?

(1) The extreme weather event was made **more likely/more severe** due to anthropogenic climate change.

(2) The extreme weather event was made **less likely/less severe** due to anthropogenic climate change.

(3) Anthropogenic climate change **did not play a detectable role** in the frequency and characteristic of the event.

(4) With our current understanding and tools, we **could not asses** whether and how the event was influenced by anthropogenic climate change.

OVERVIEW

1) What is climate attribution science?
2) **Weather as complex phenomenon**
3) How is it done in practice?
4) Conclusion and Outlook

‘COMPLEX’ – BUT WHAT DOES THIS MEAN?

- Reductionism – dominating approach in the 20th century

→ The complex world is **nothing but** the sum of its parts.

- Complexity – dominating approach in the 21st century?

→ The complex world is **more than** the sum of its parts.

[7]

Concretely: Complexity is the study of systems consisting of many interacting units that give rise to emergent behaviour which cannot be understood by studying a single unit in isolation. [Ref. A]

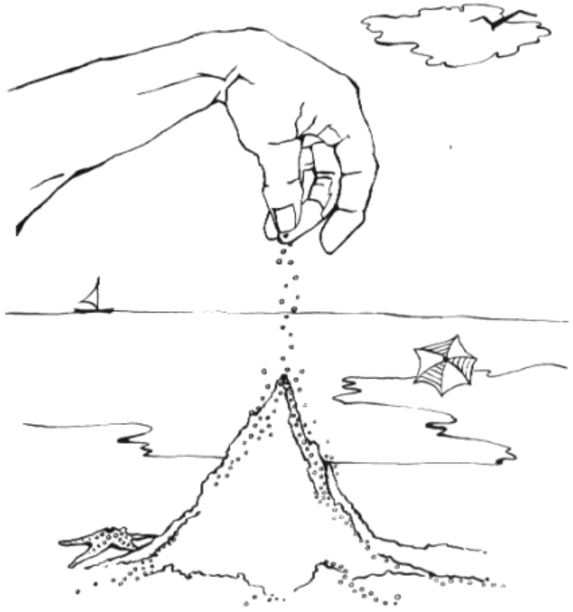
THE SAND PILE METAPHOR

Build a sand pile on a table of **finite size L** using:

1. Add a sand grain to the first site $(i = 0)$
2. If the **local slope z_i** at site i exceeds **critical slope $z_{i,crit}$** :

   → let grain topple down to next site

   → assign new critical slope to site i : $z_{i,crit} \in \{1, 2\}$
3. Repeat.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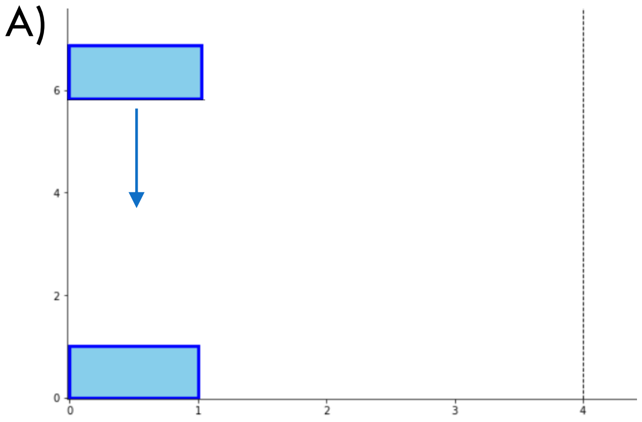

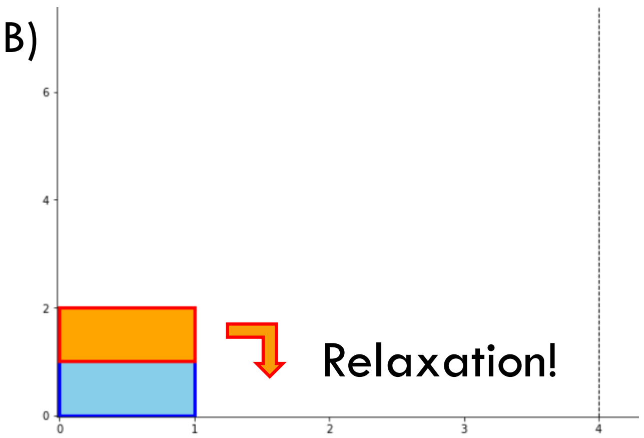

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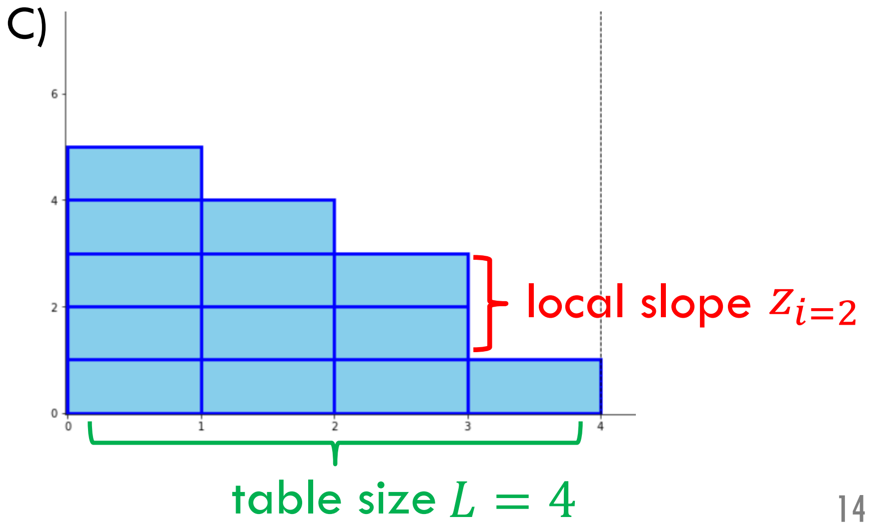

DEMONSTRATION – BUILDING UP THE SAND PILE

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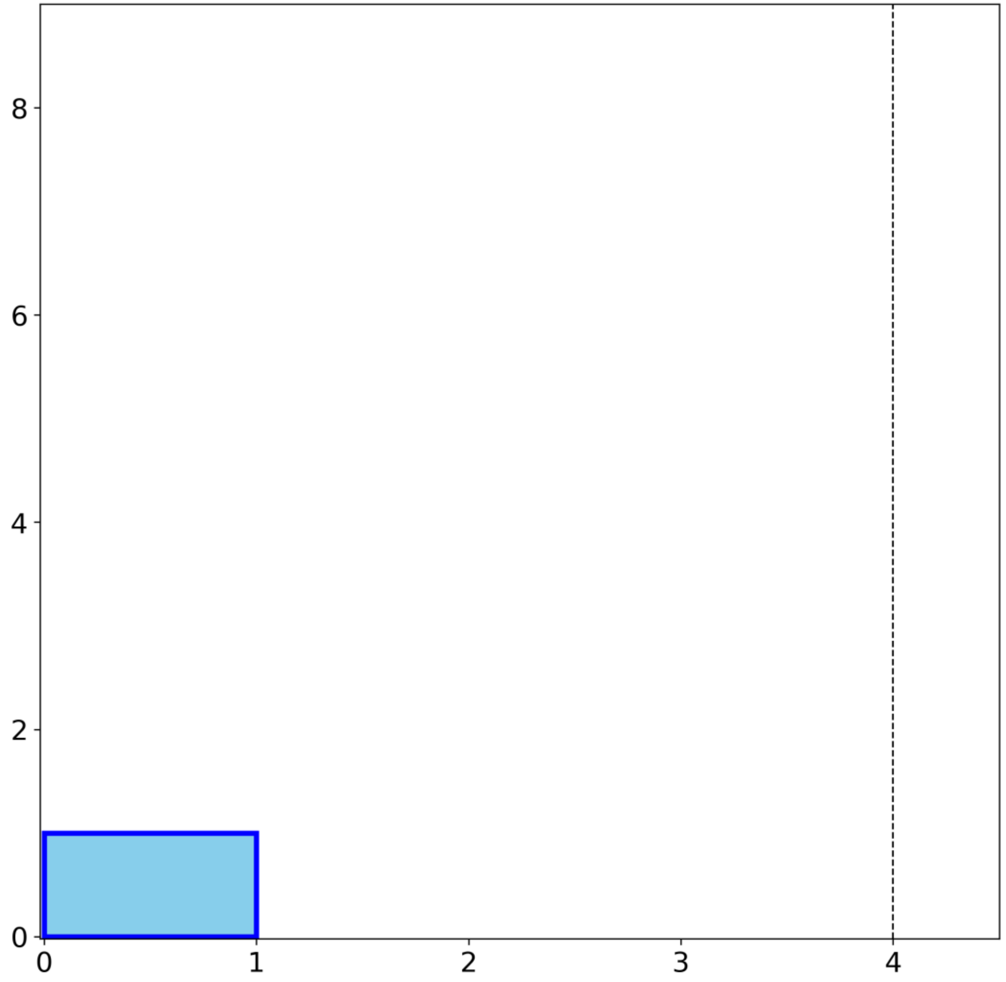

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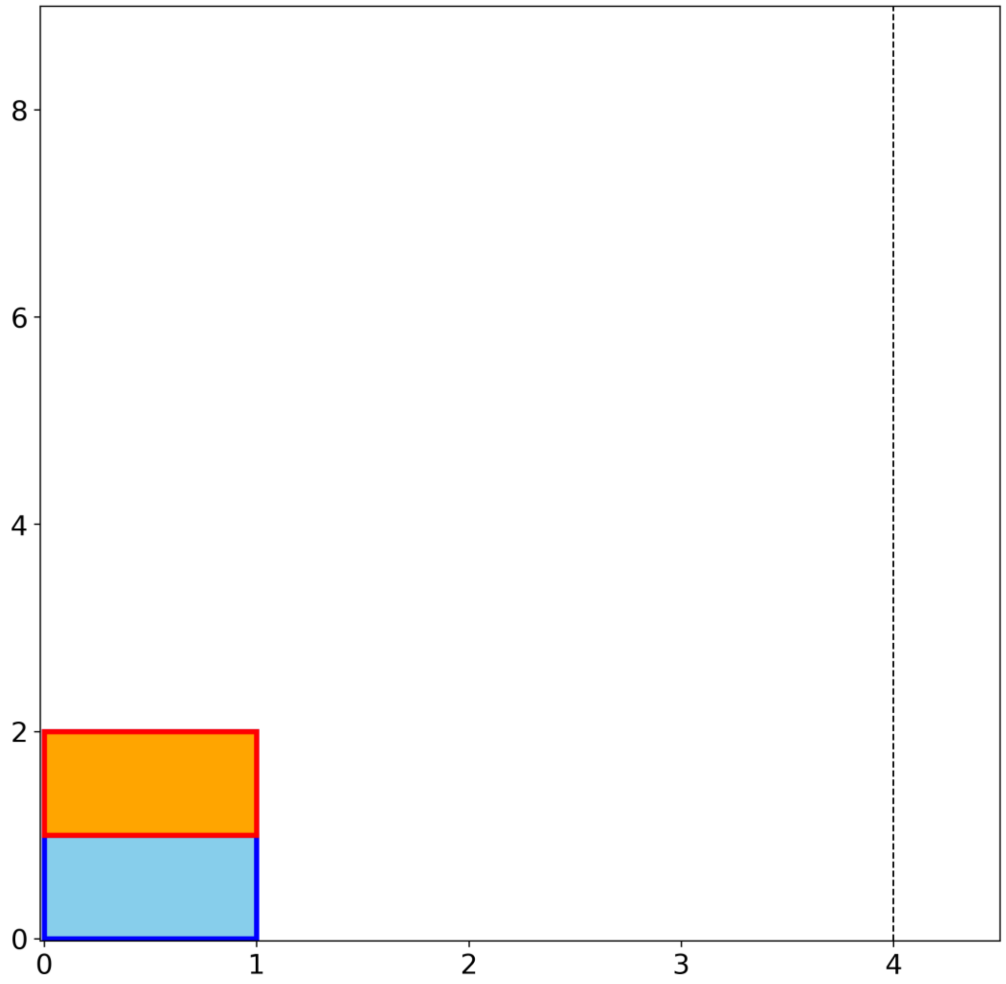

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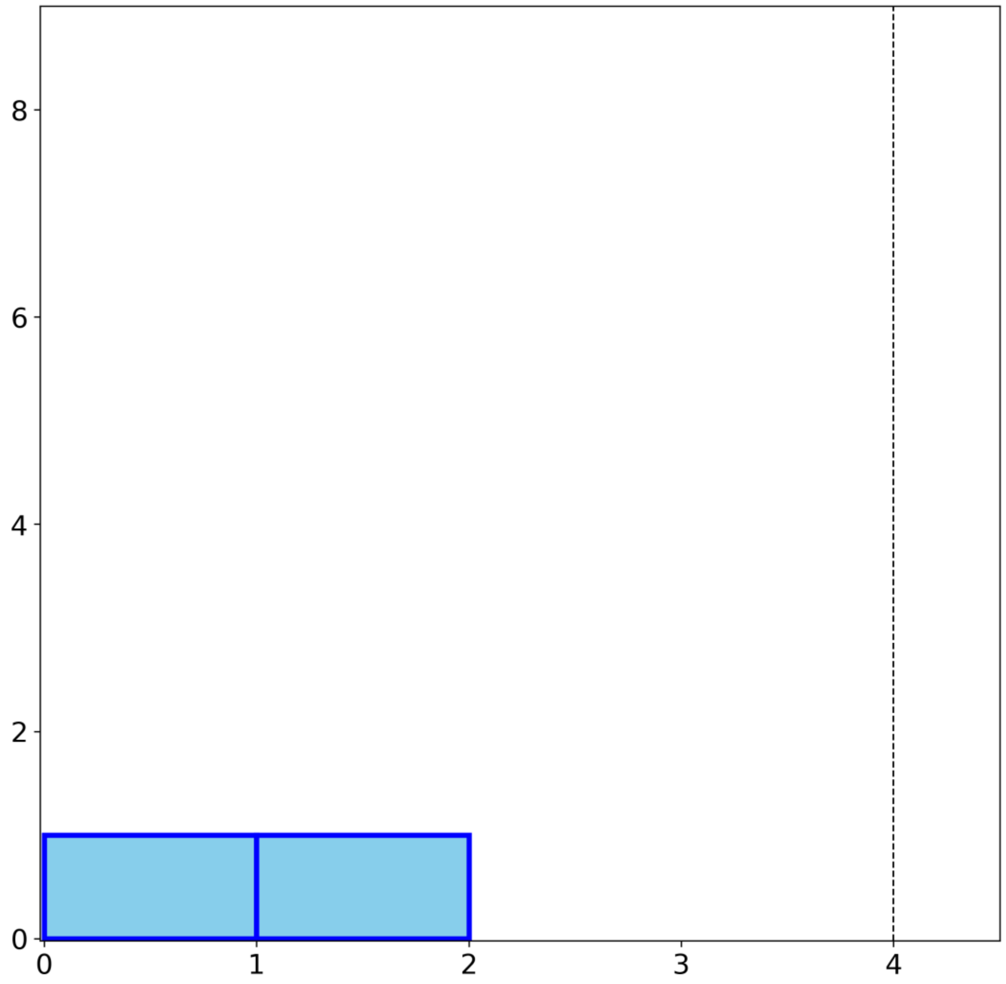

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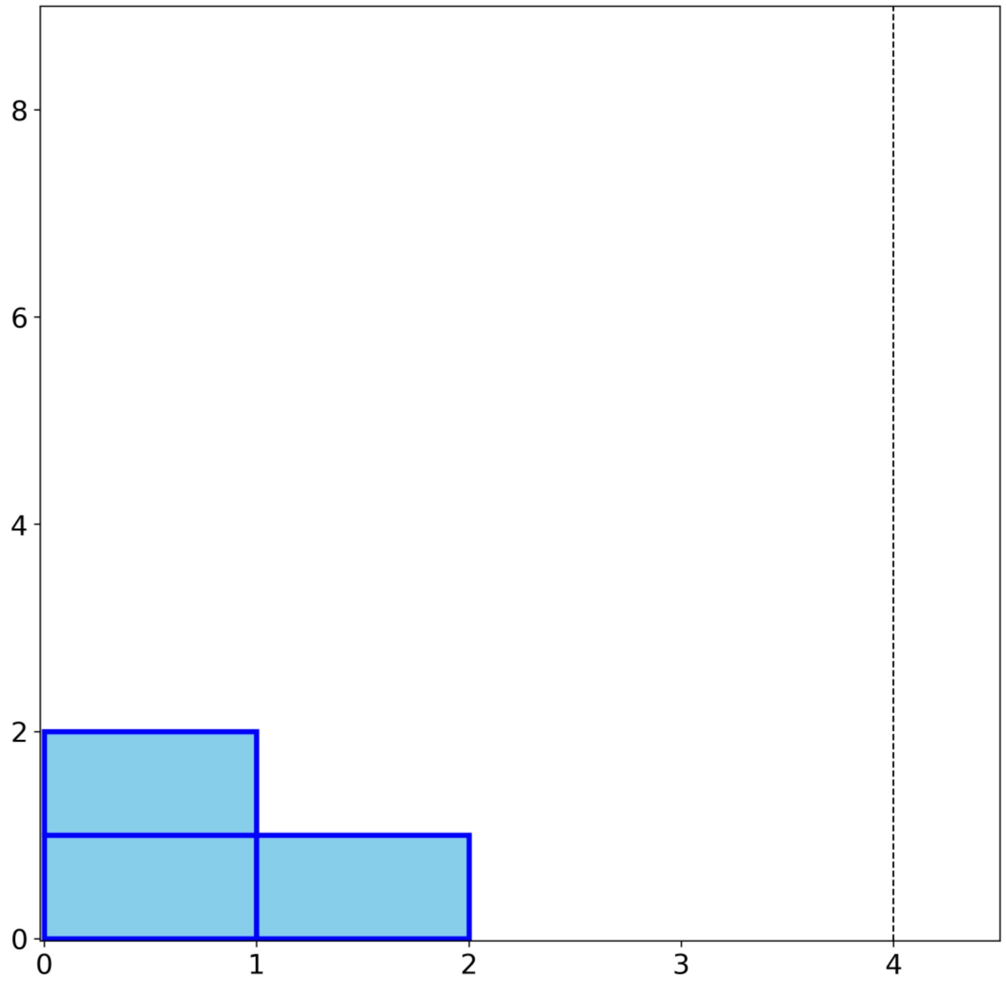

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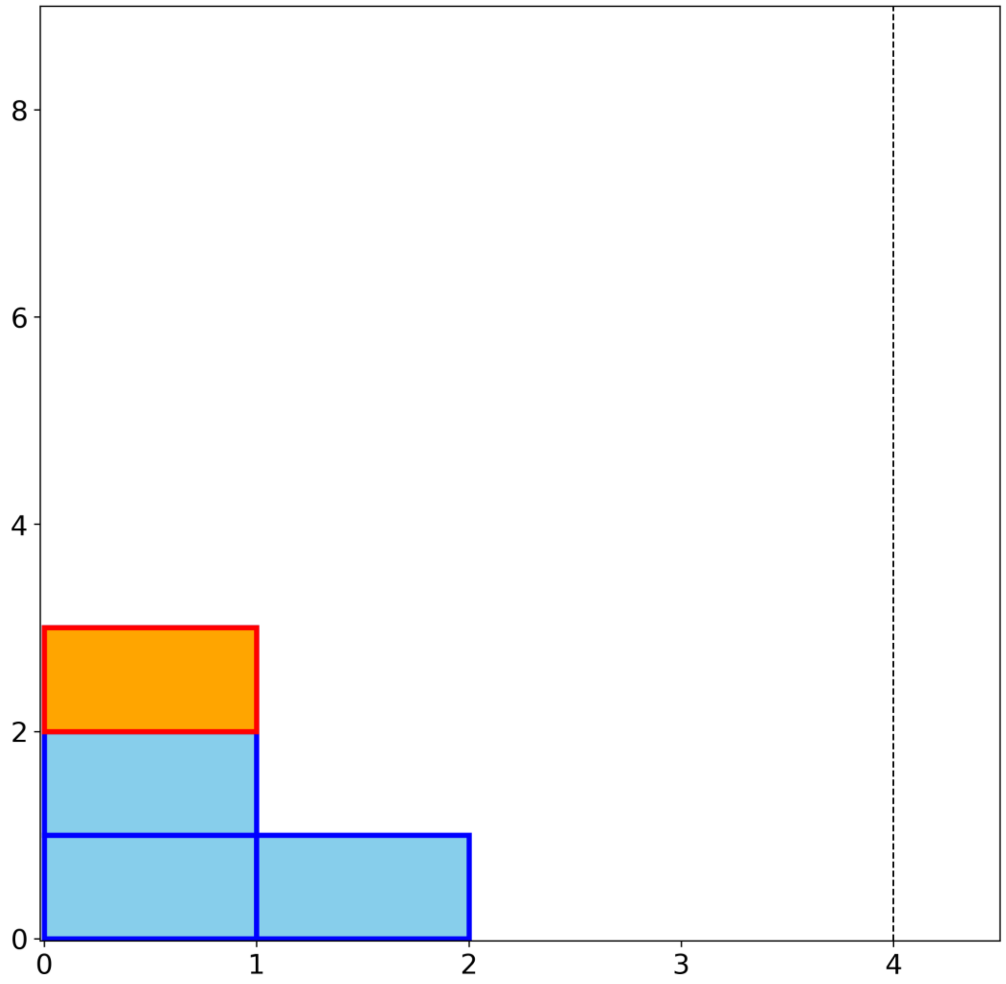

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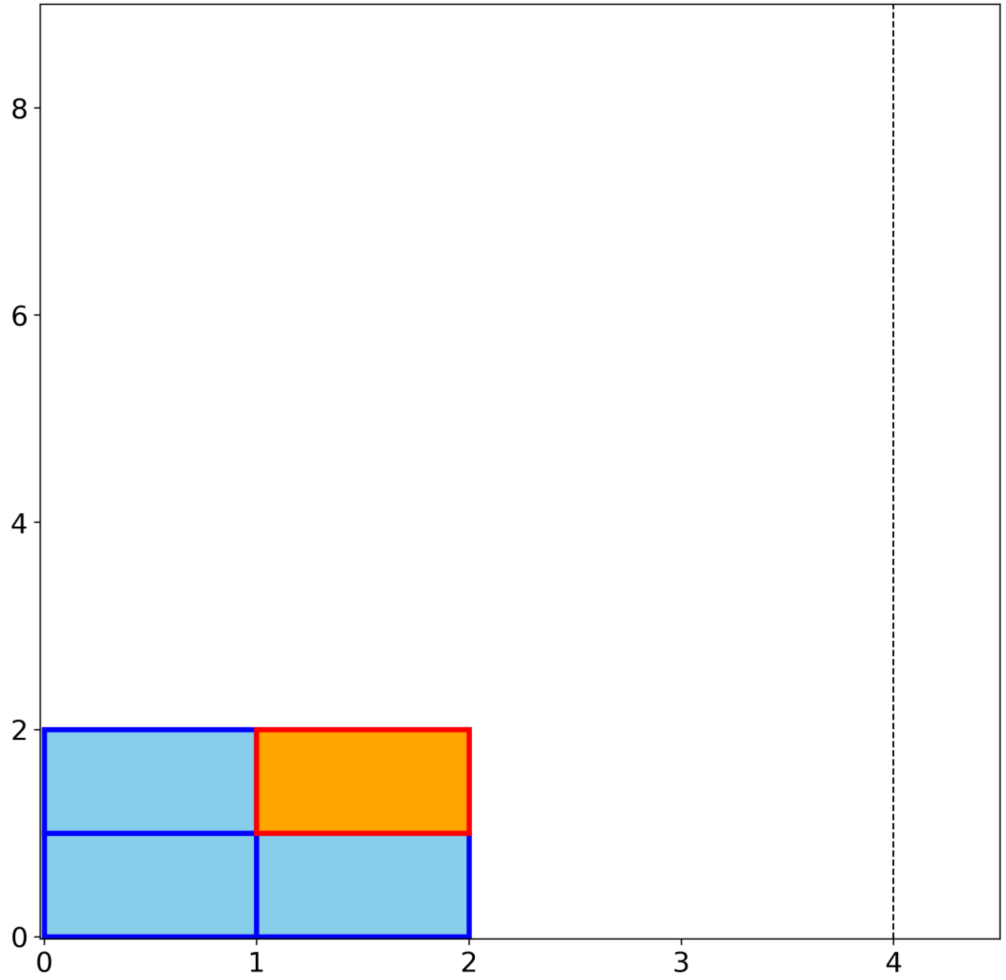

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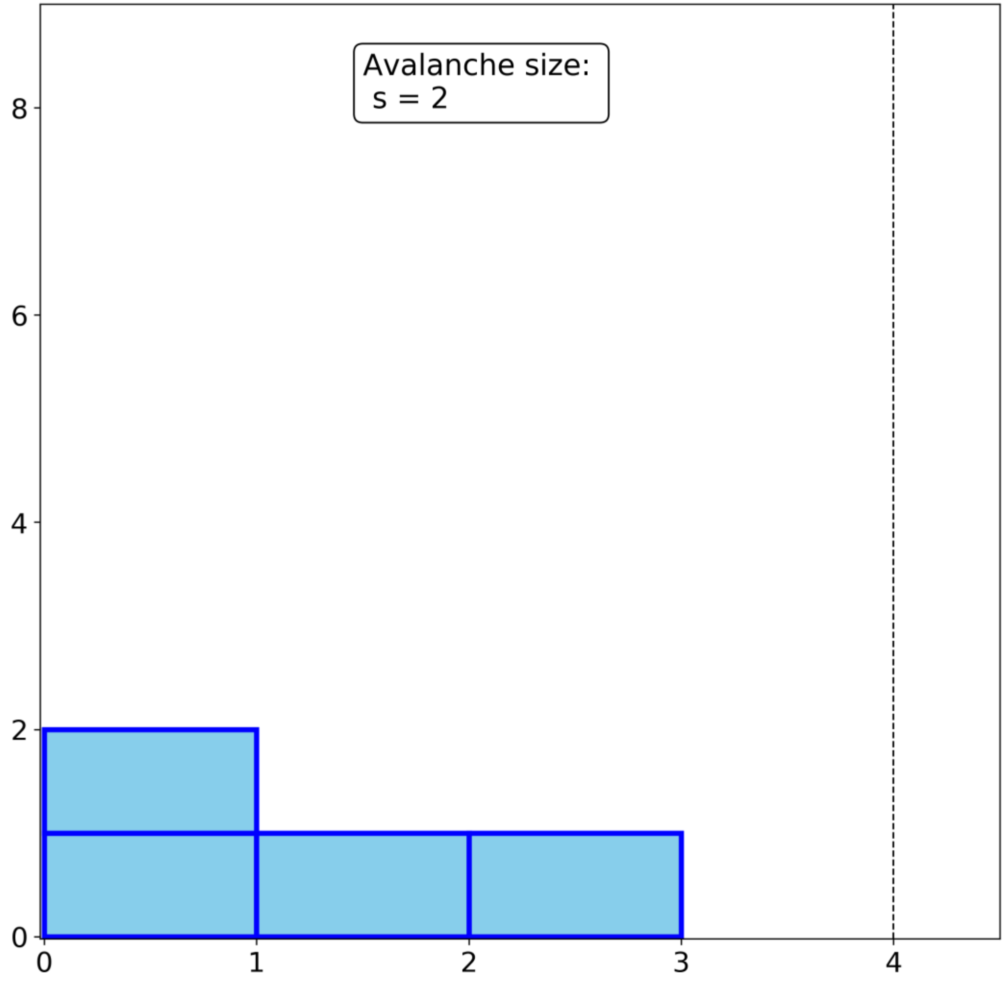

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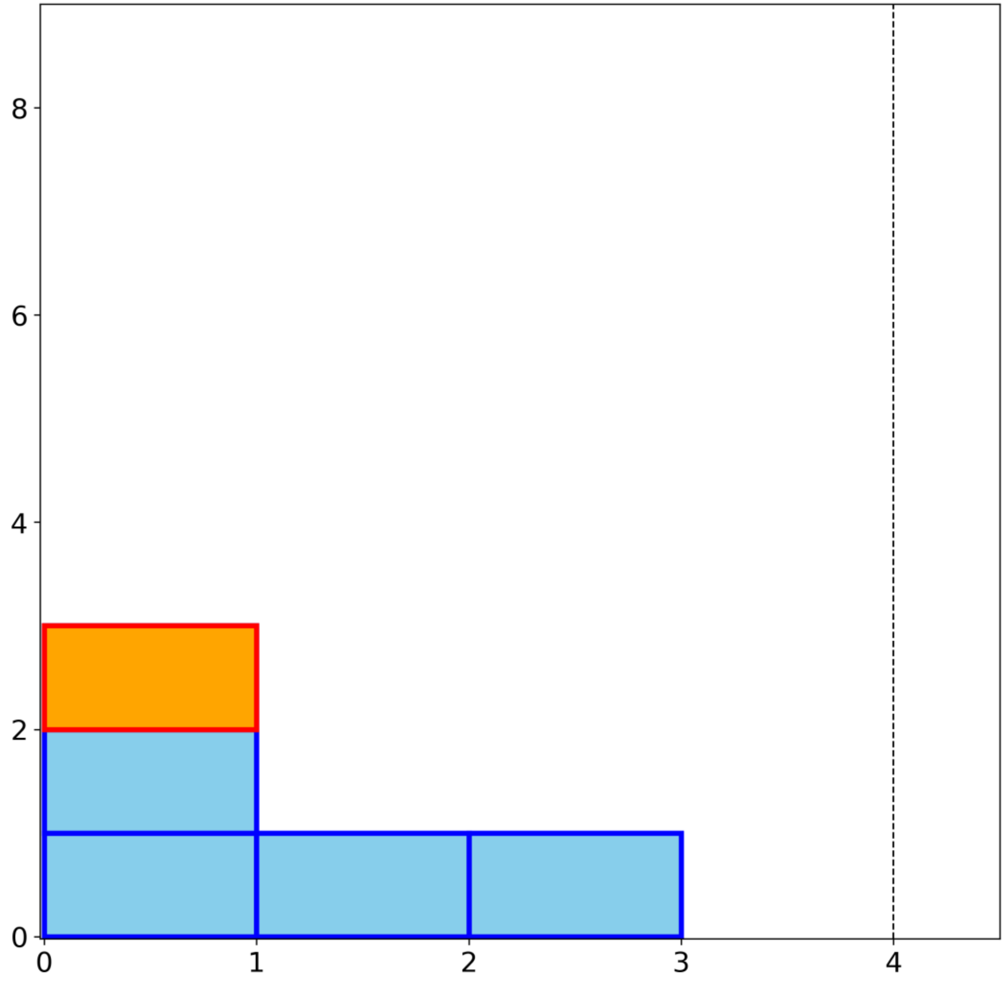

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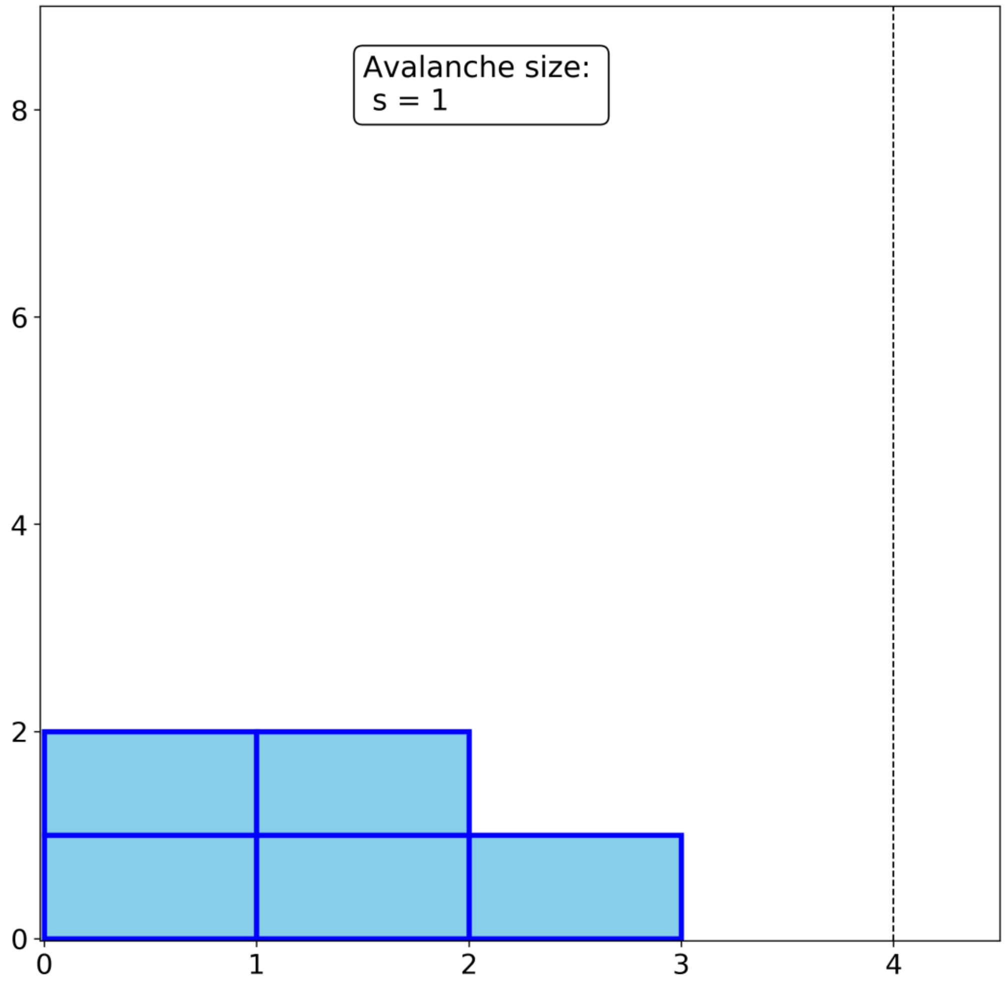

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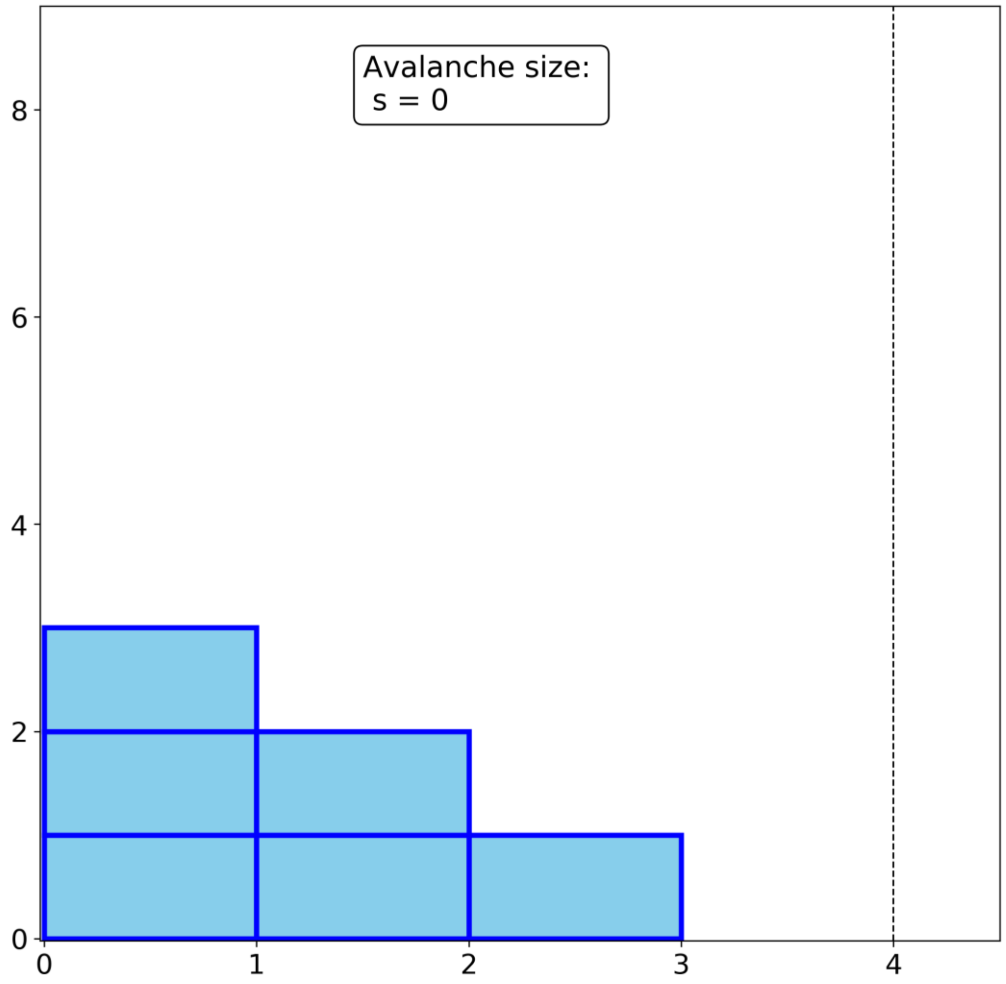

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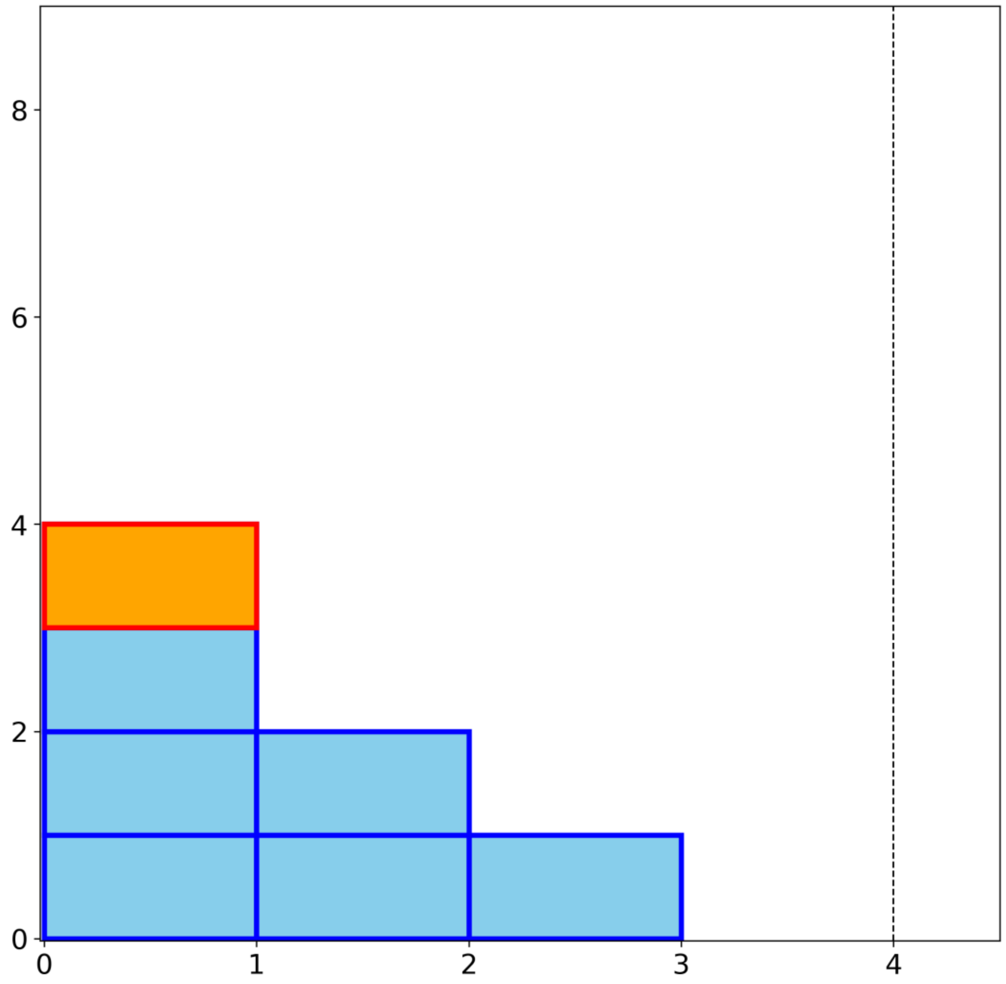

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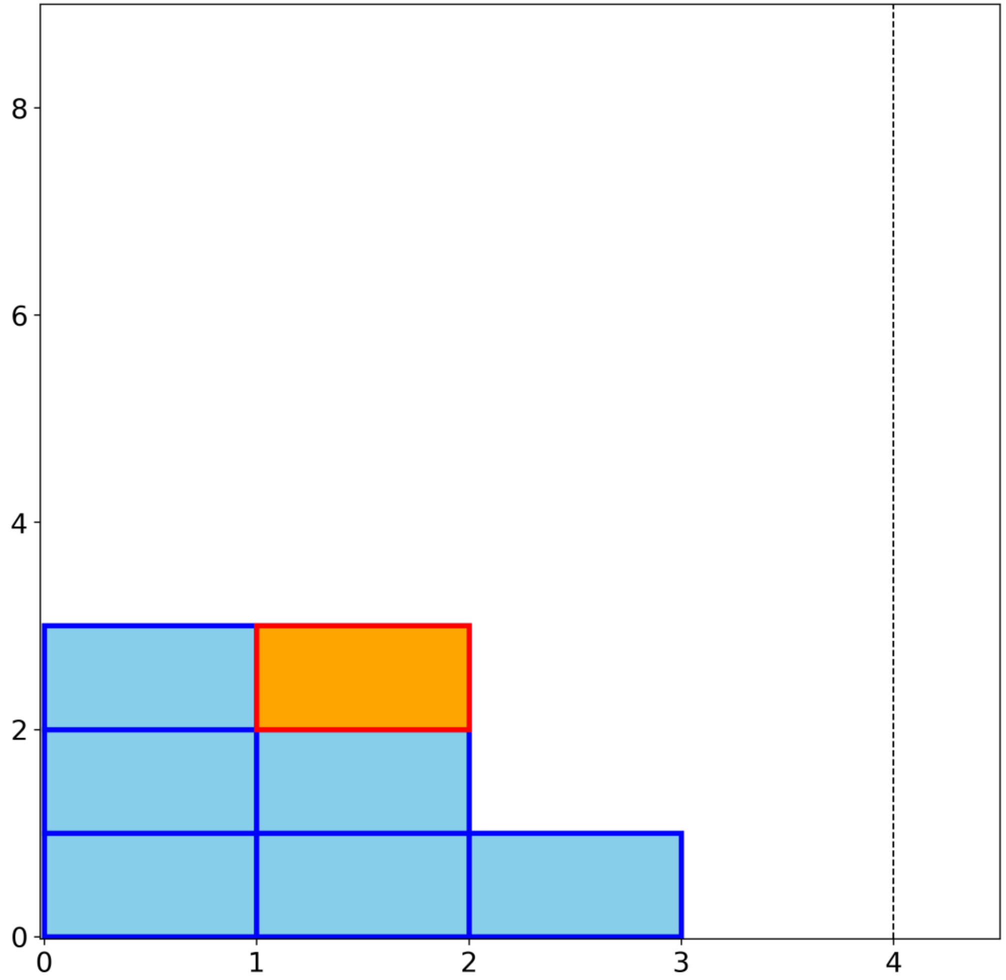

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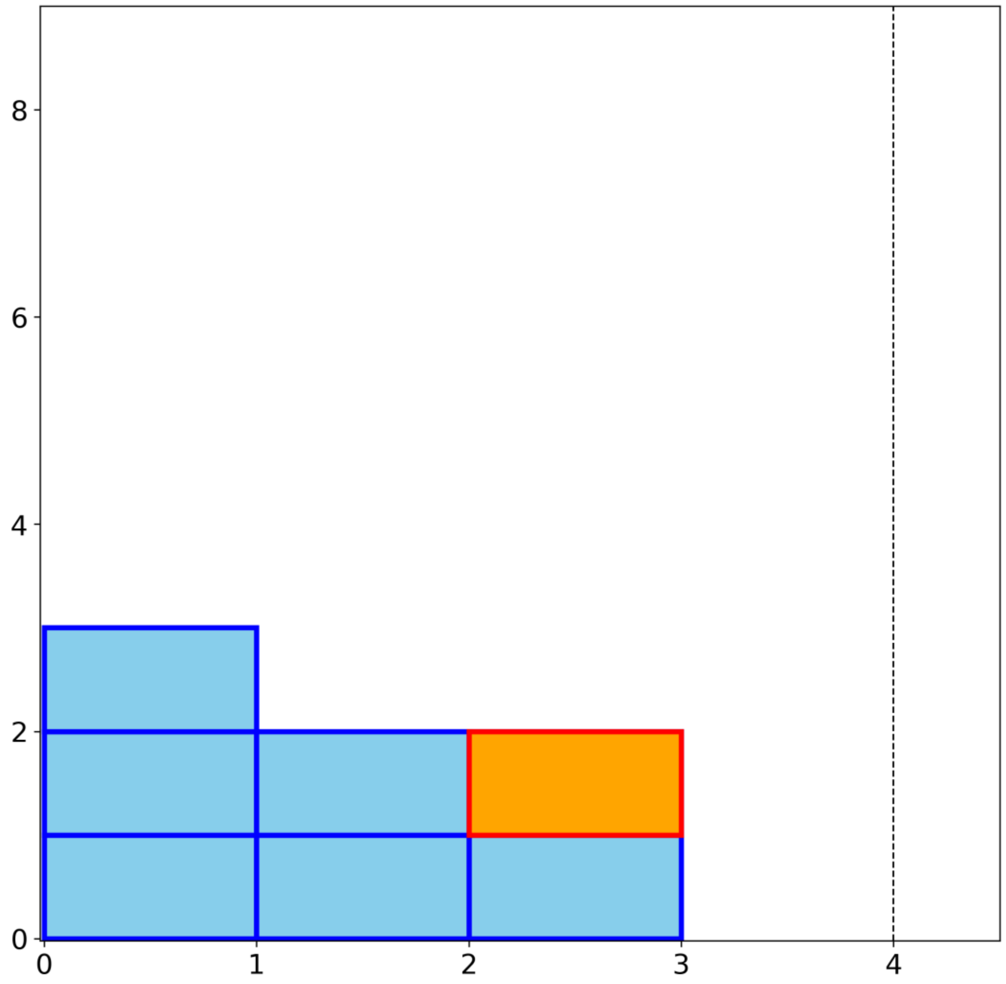

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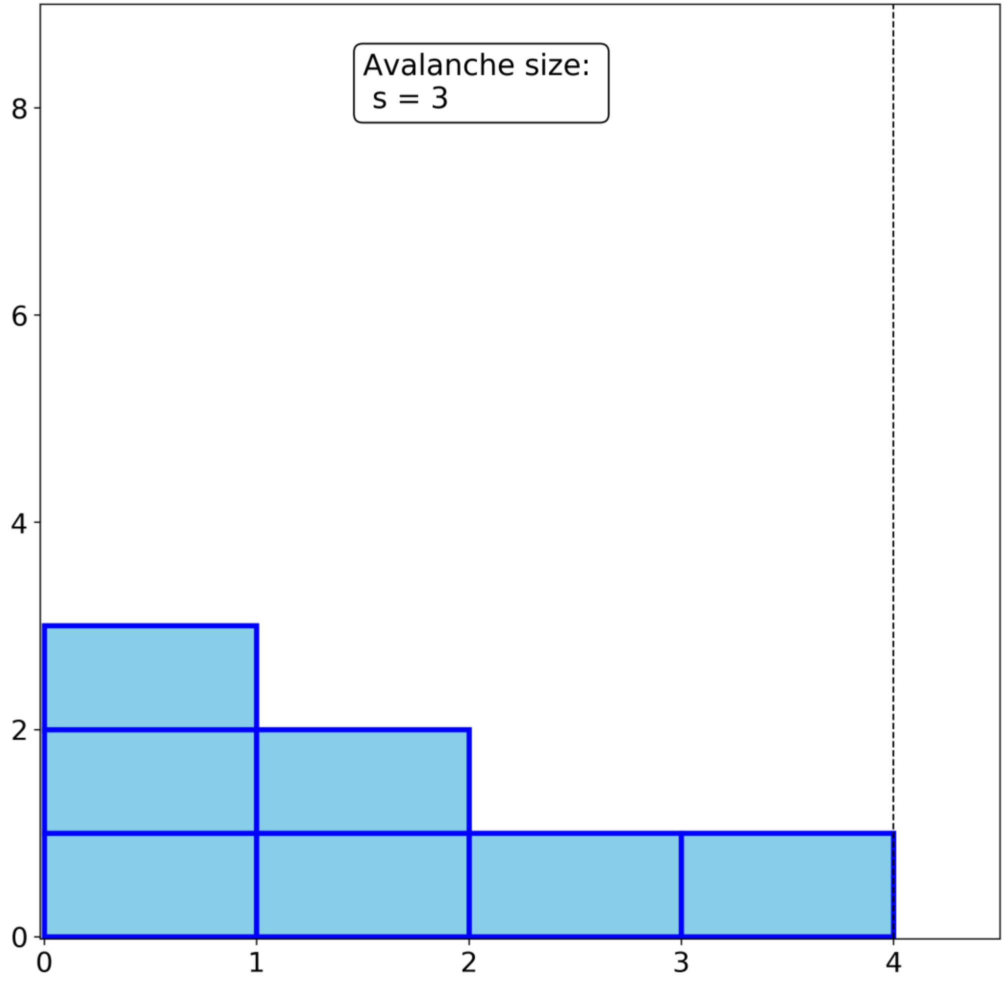

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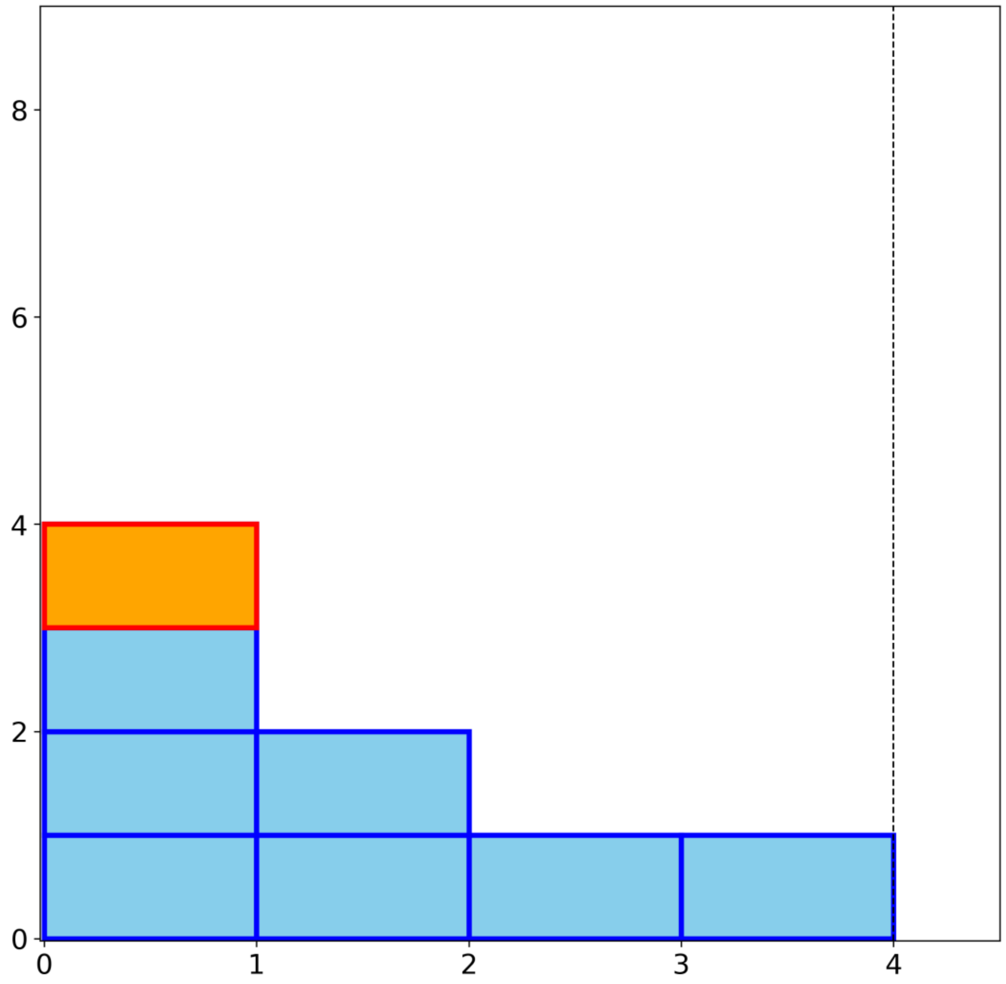

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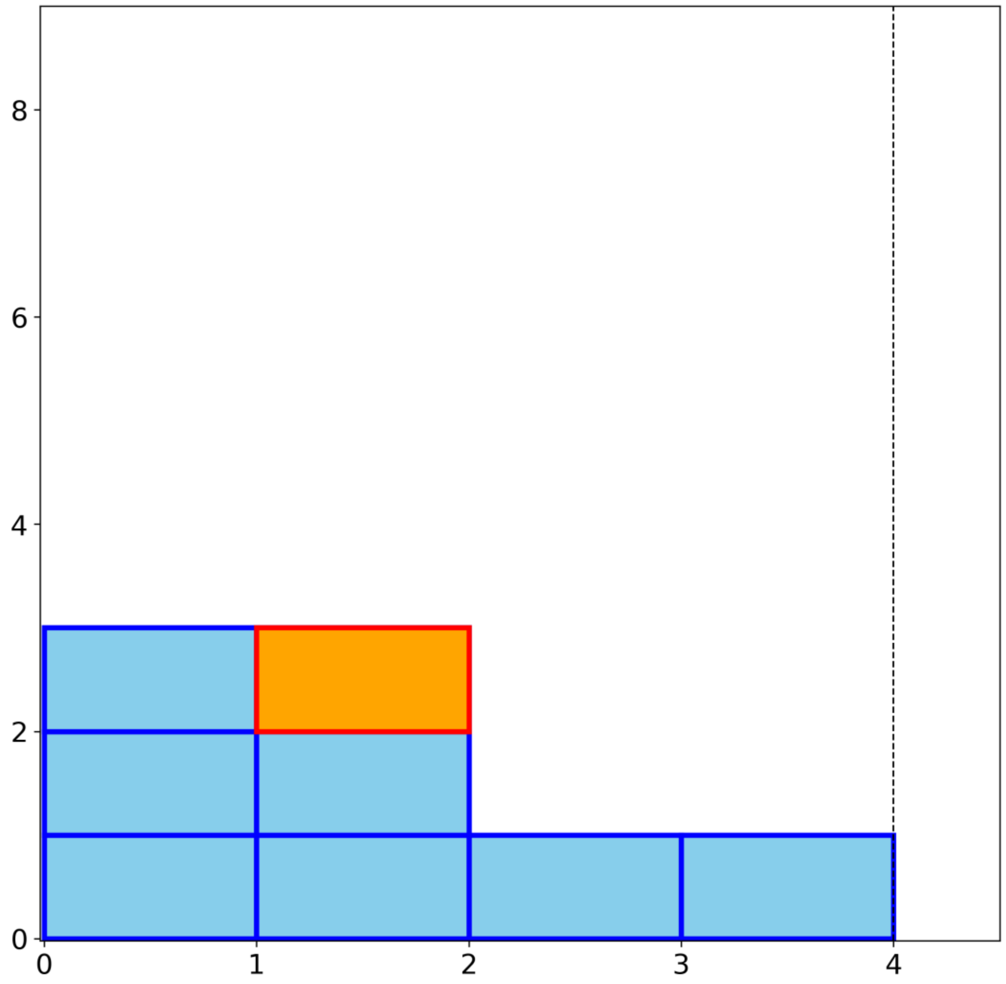

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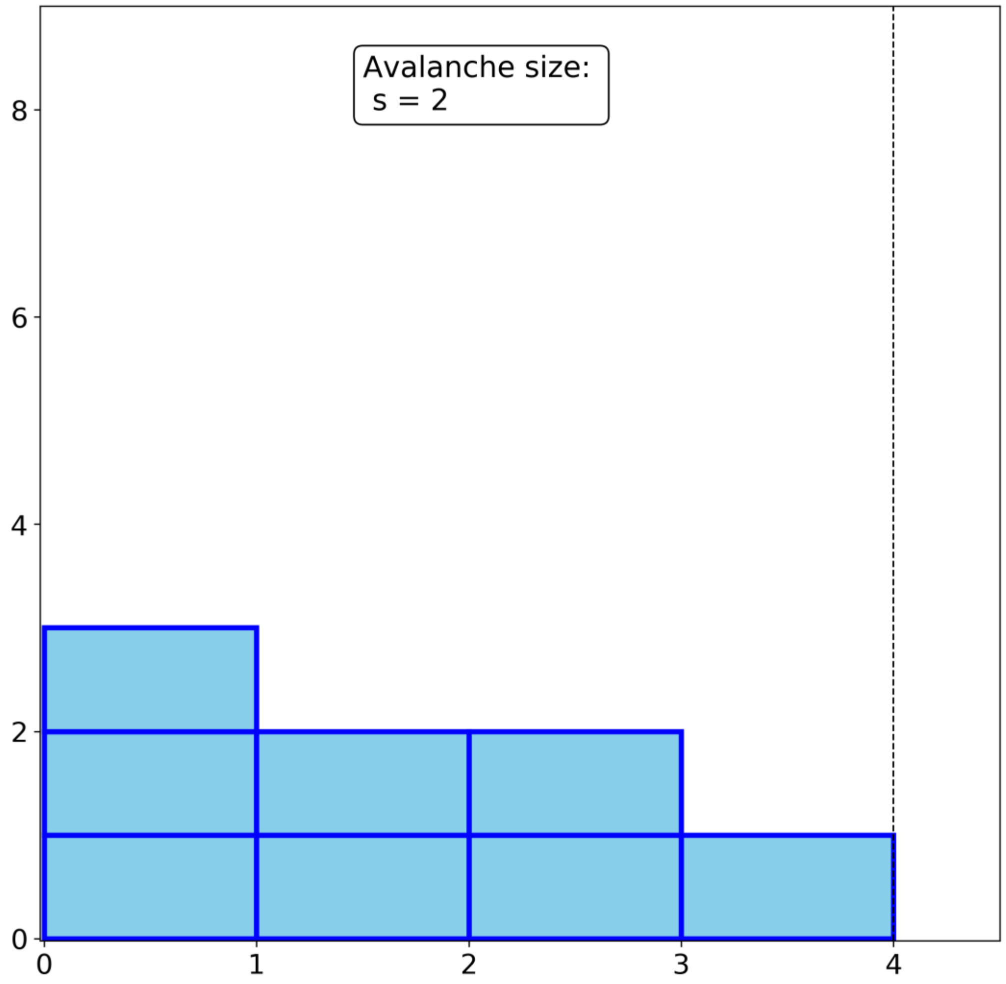

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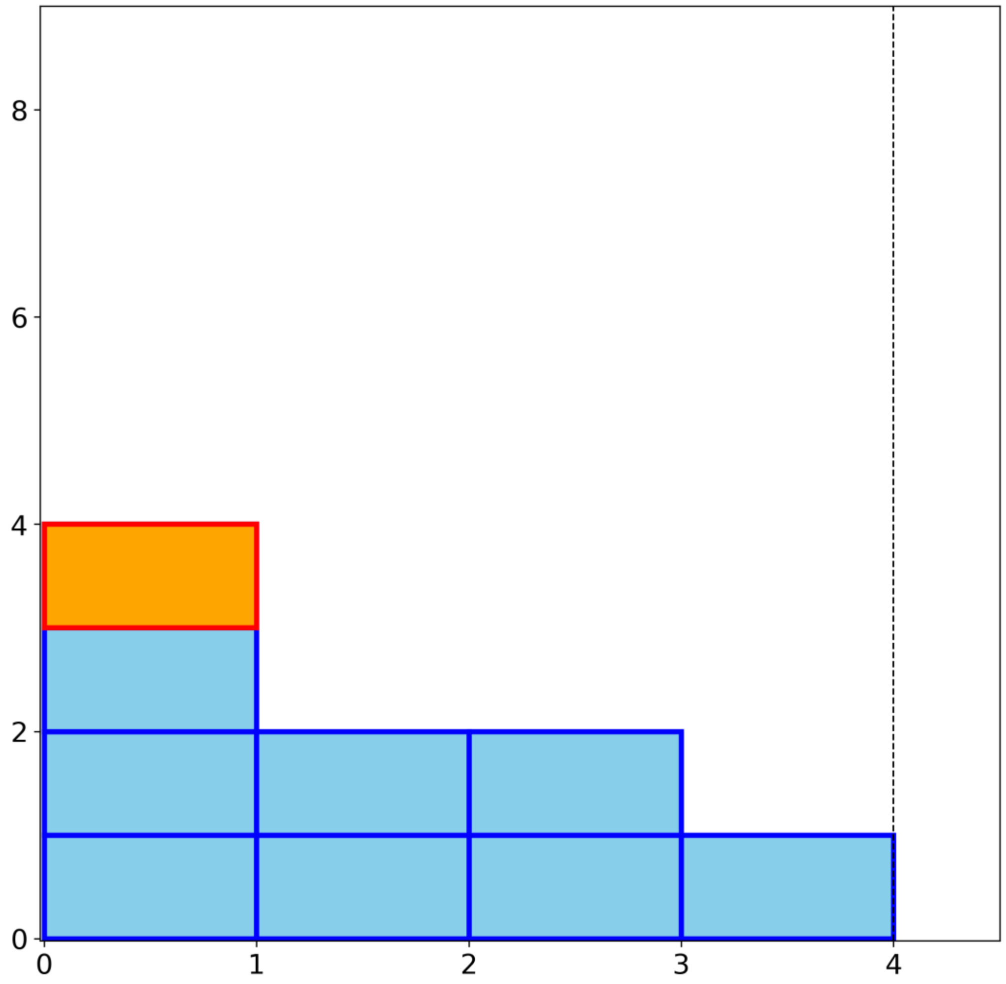

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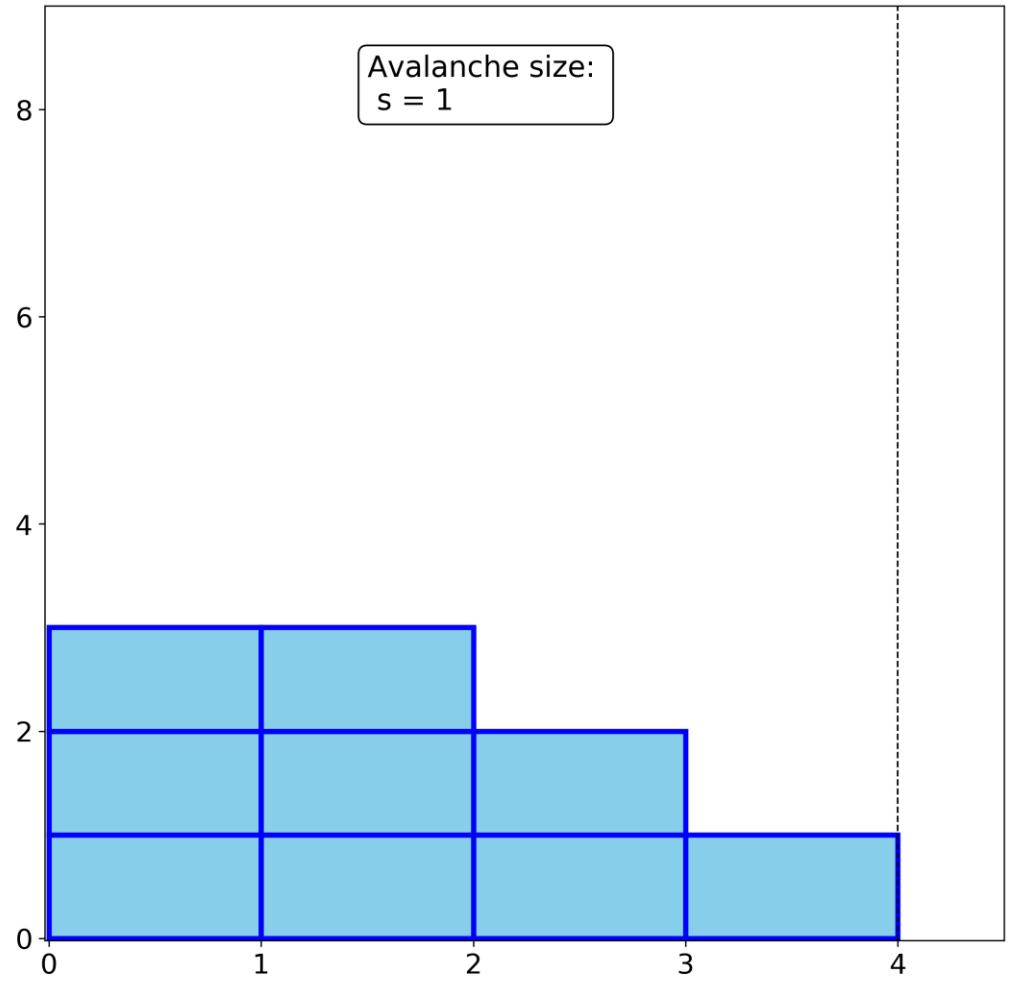

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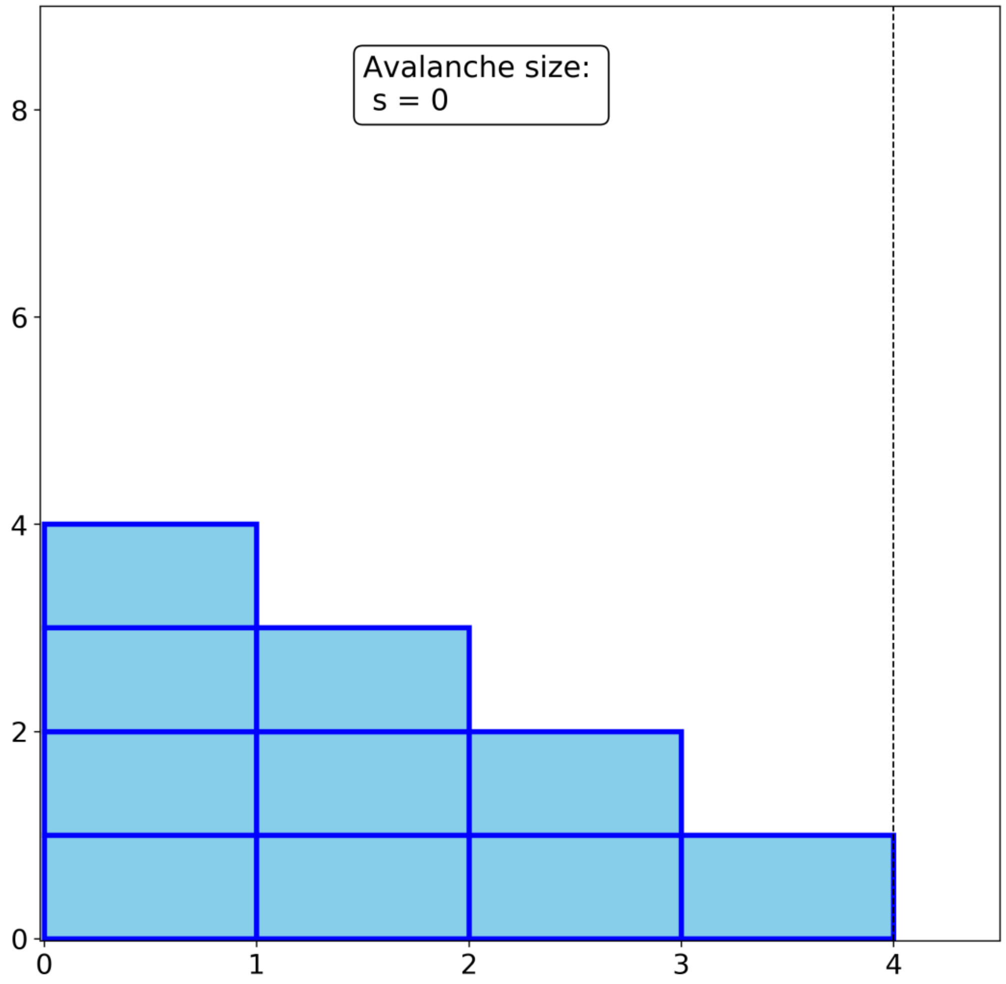

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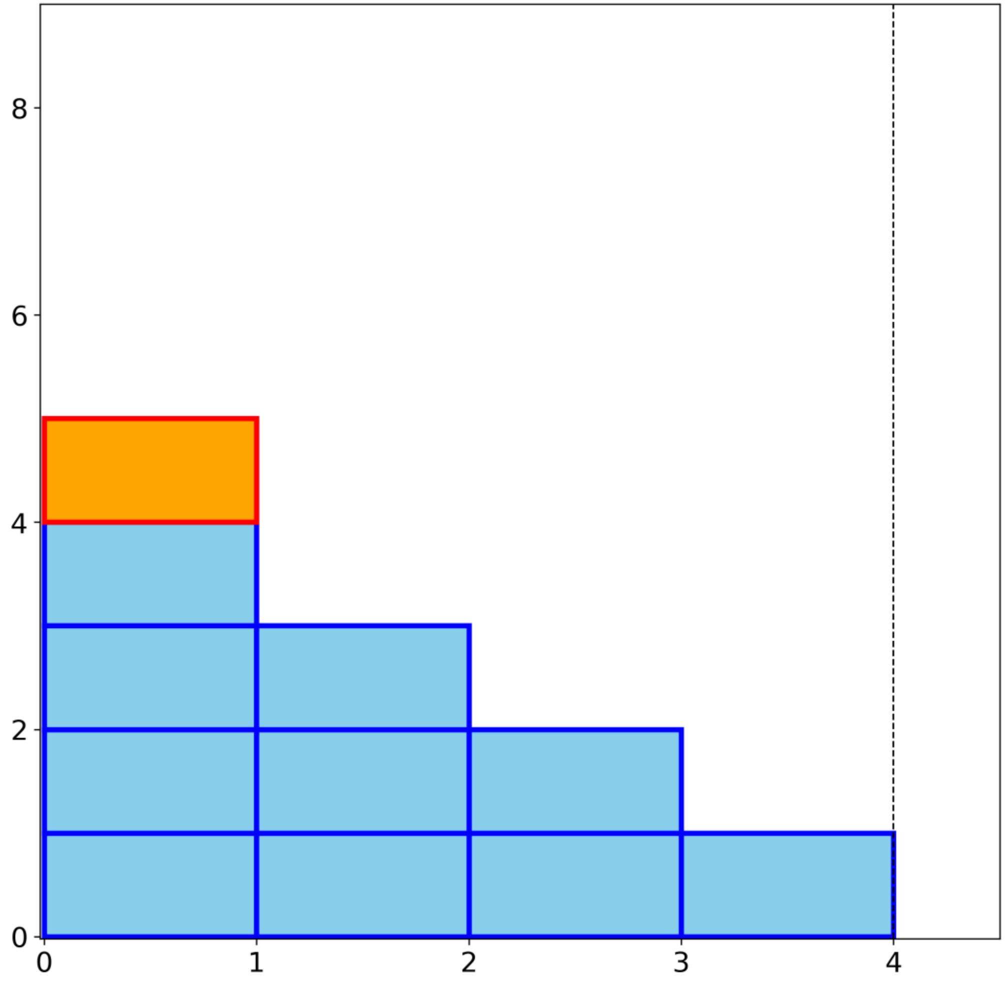

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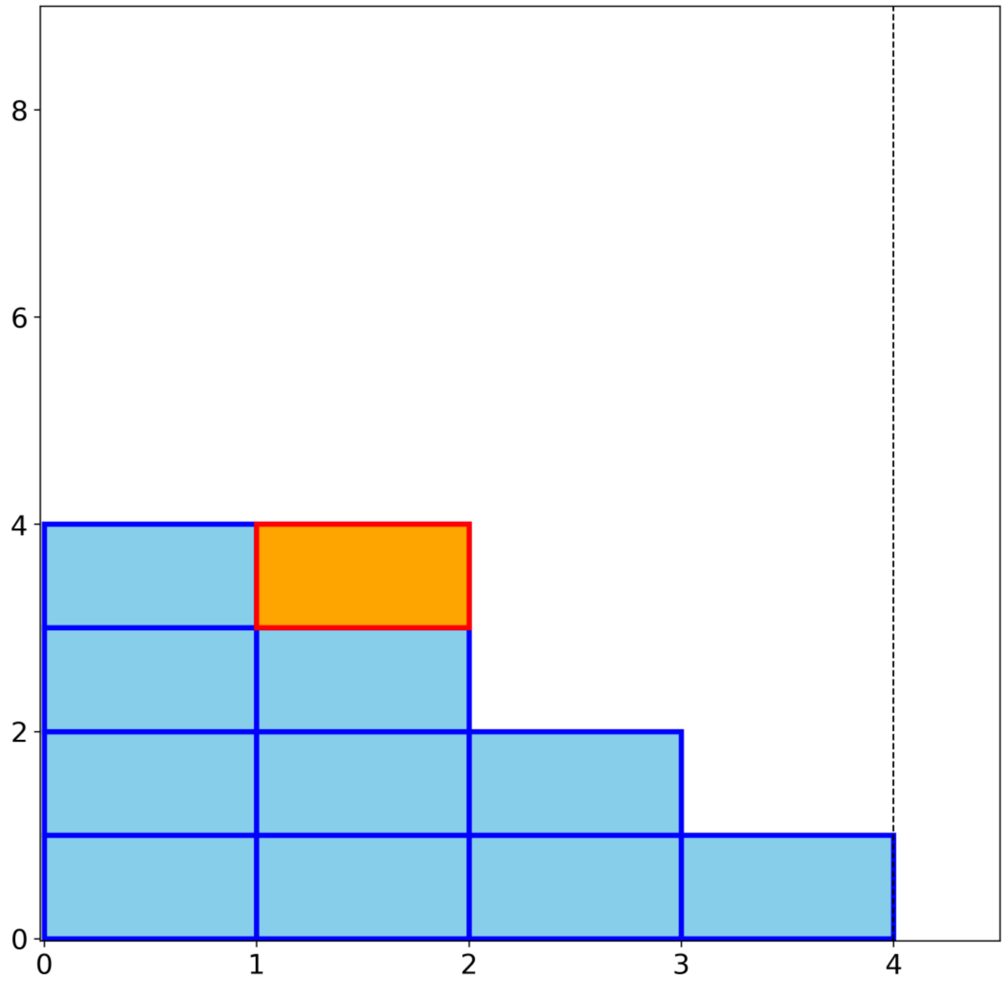

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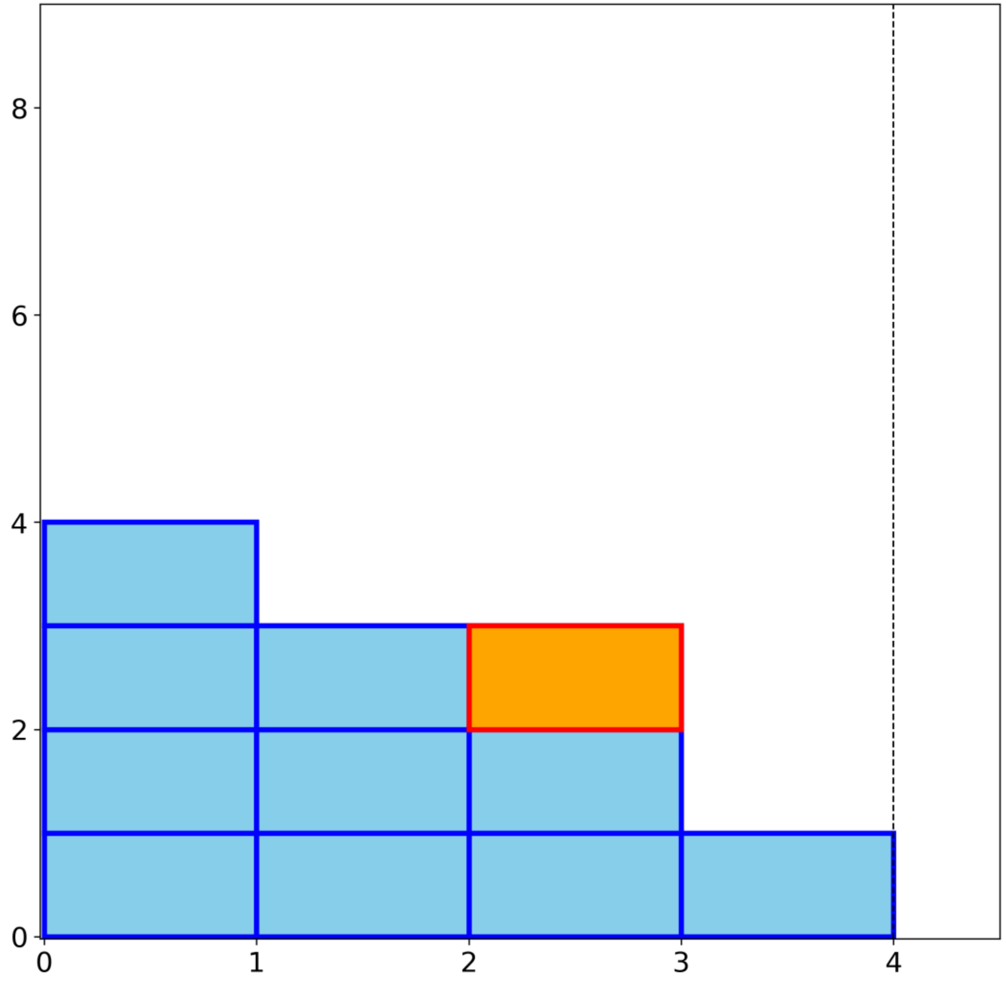

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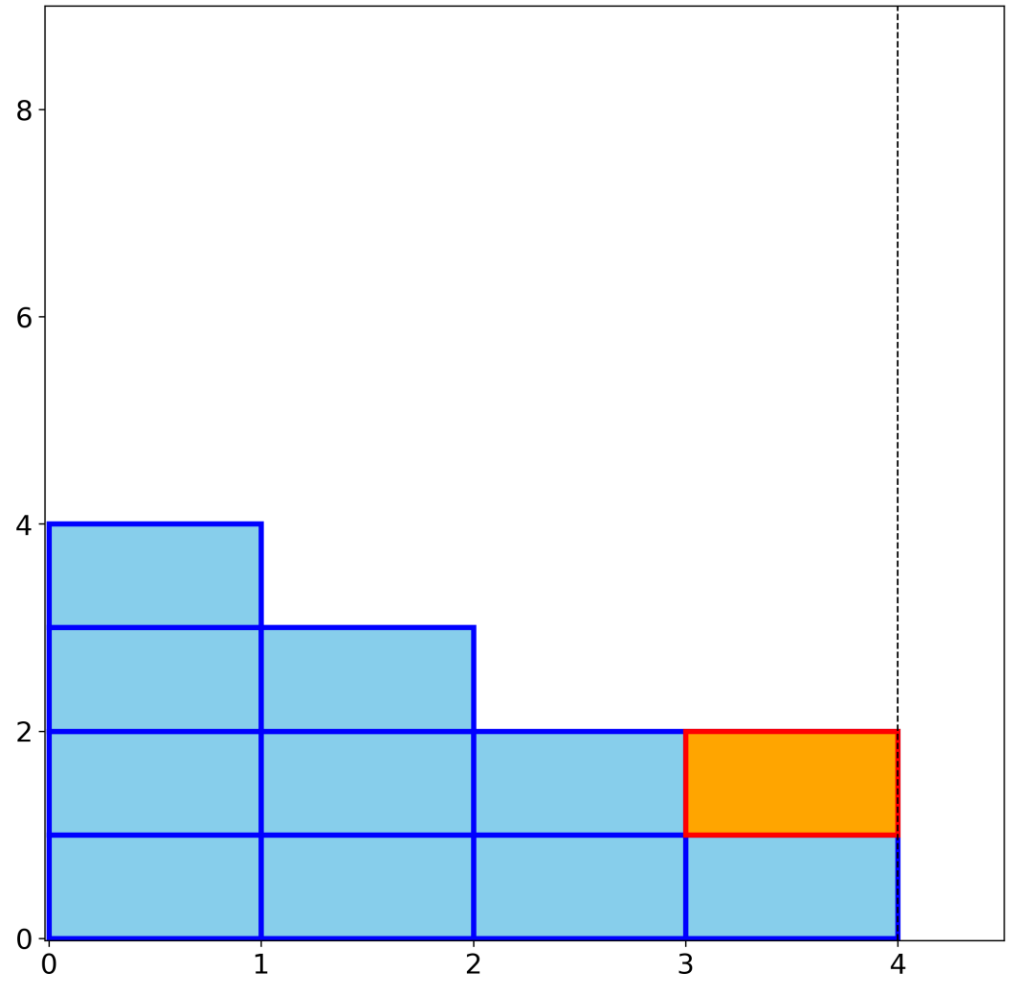

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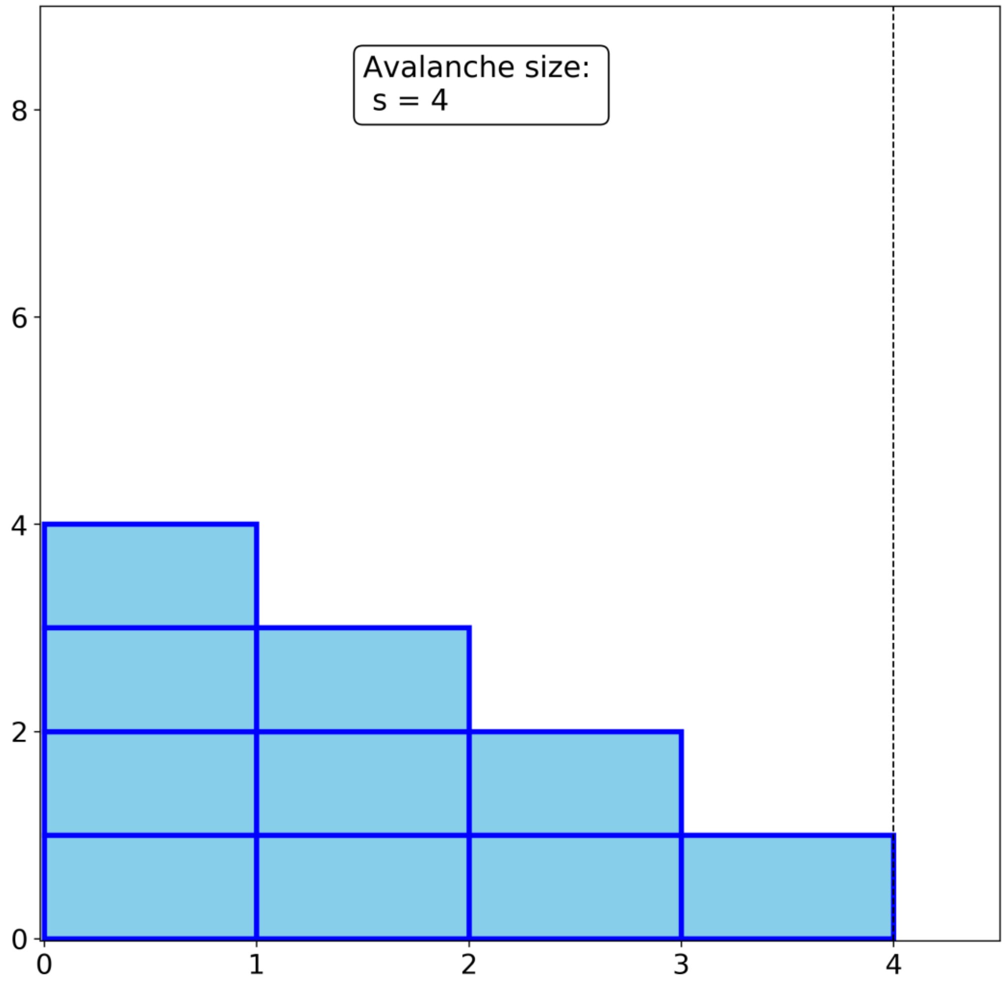

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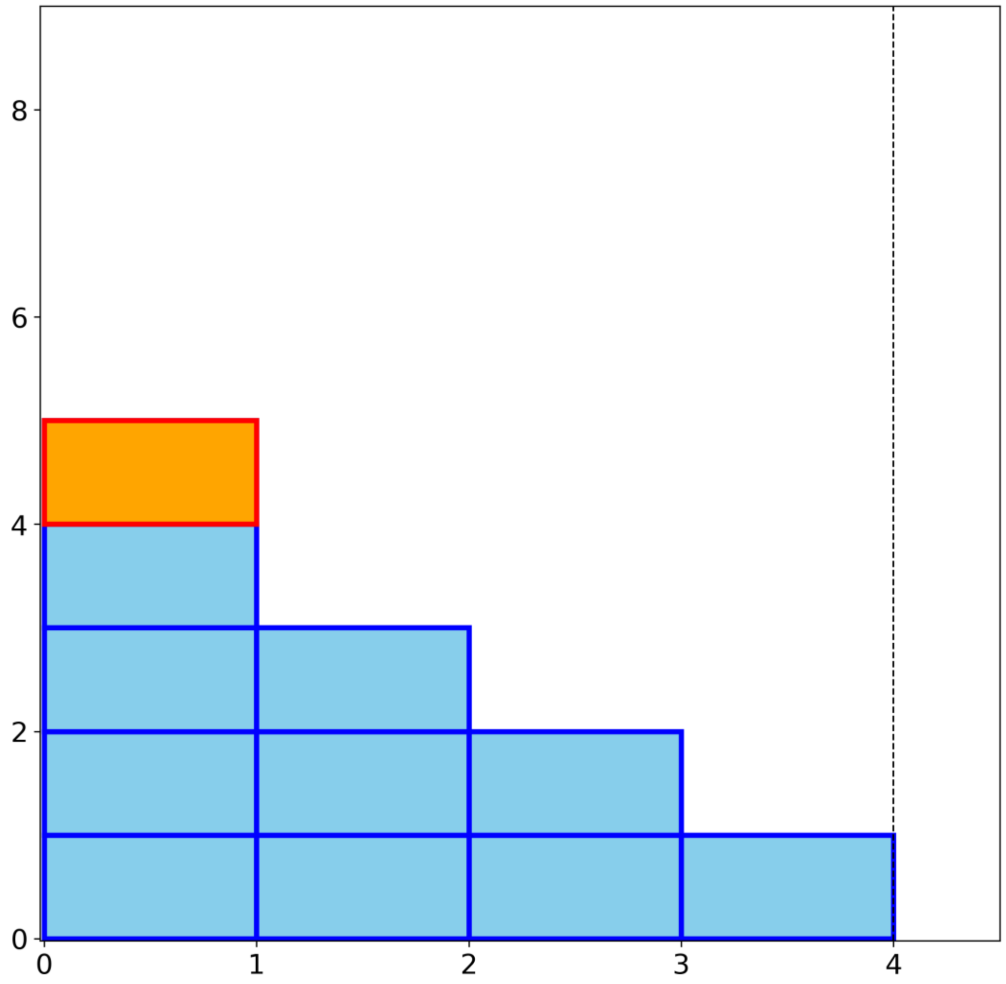

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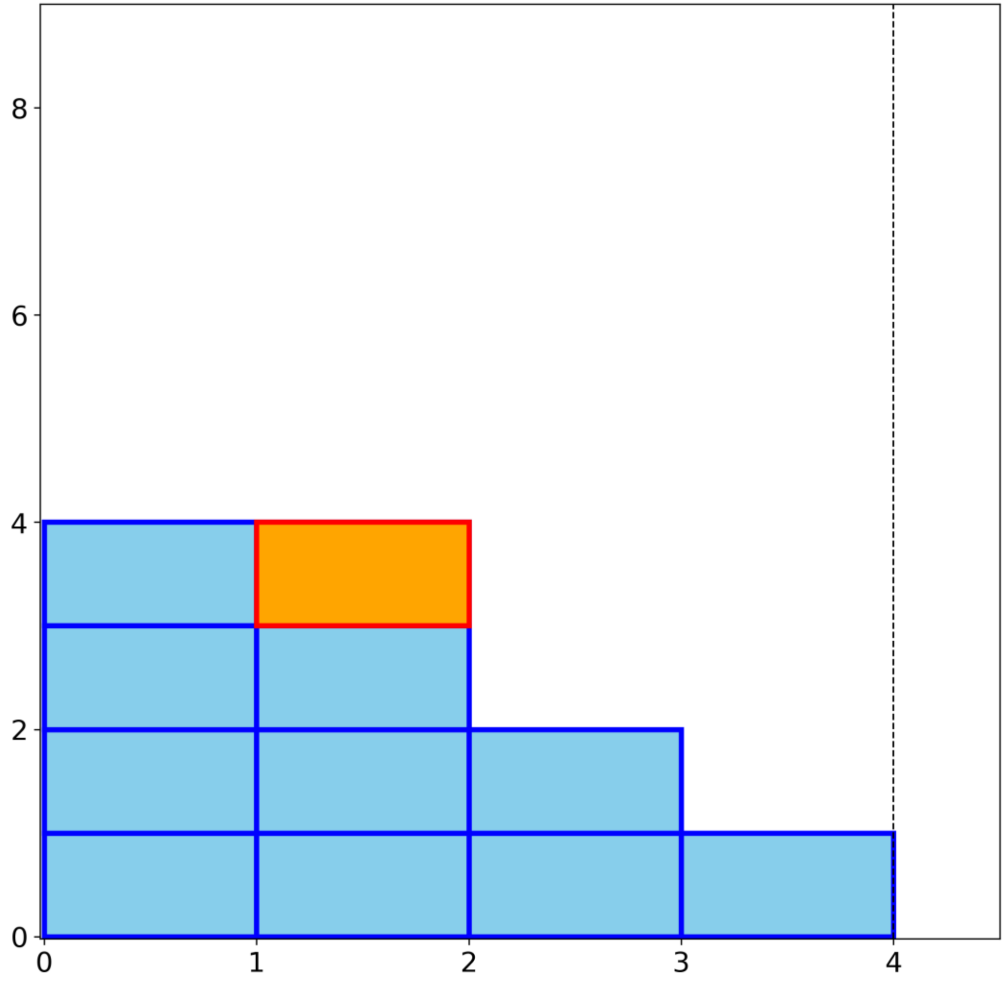

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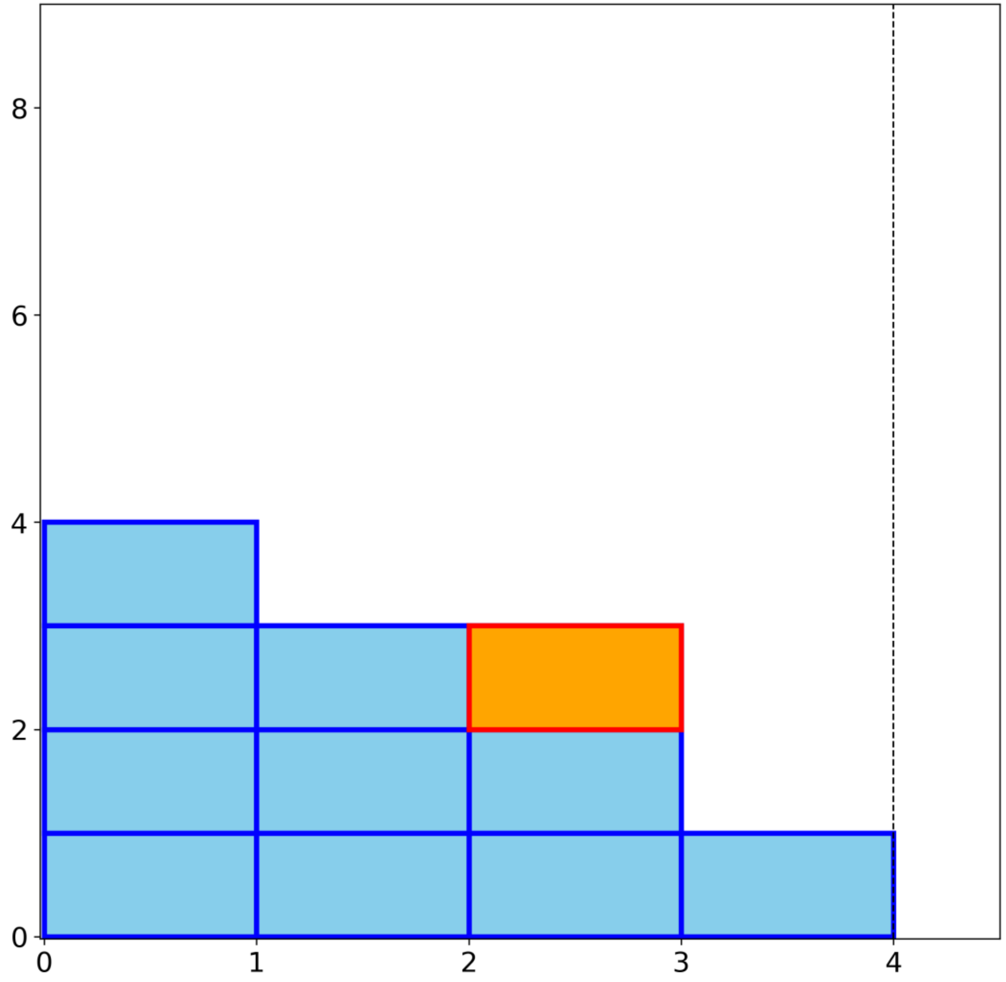

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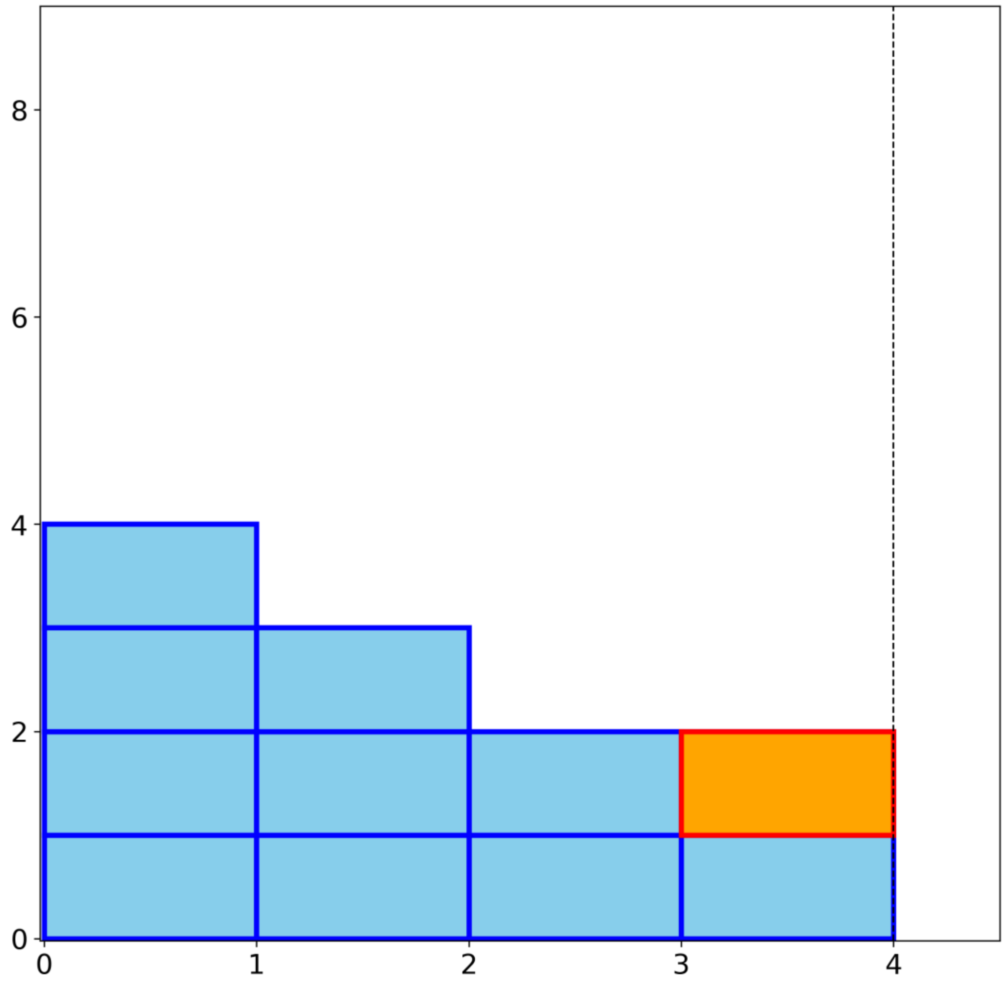

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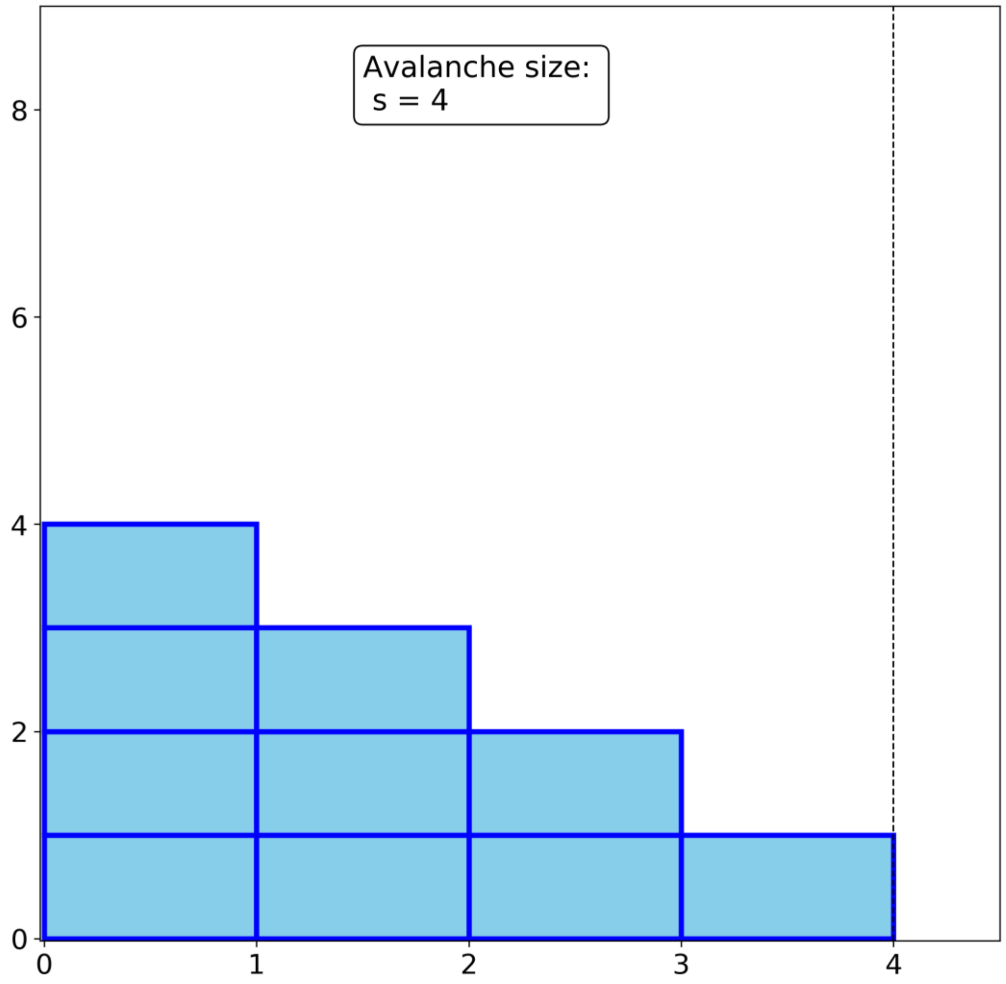
→ **This model behaves trivially in the *steady state*.**



DEMONSTRATION – NON-TRIVIAL AVALANCHES

Now, choose critical slopes randomly with

- $P(z_{i,crit} = 1) = 1/2$
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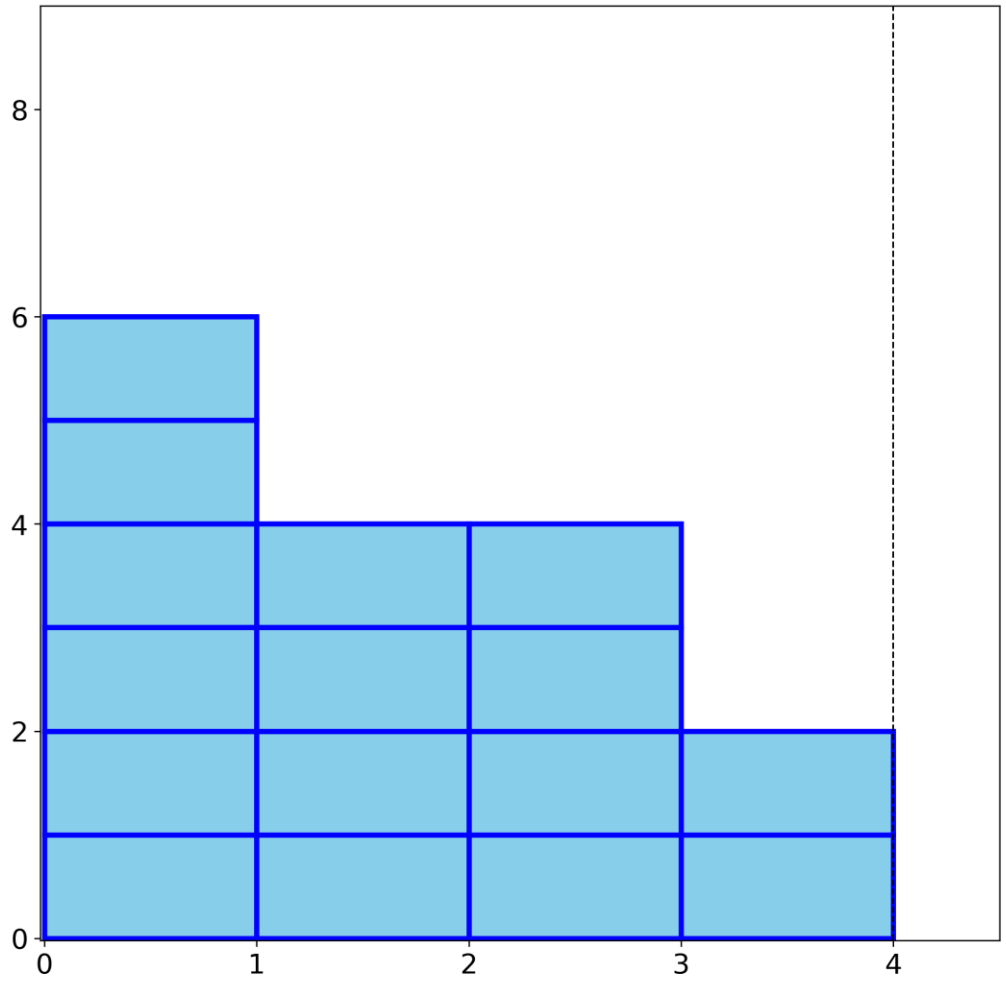
After building up the sand pile, find a configuration like this



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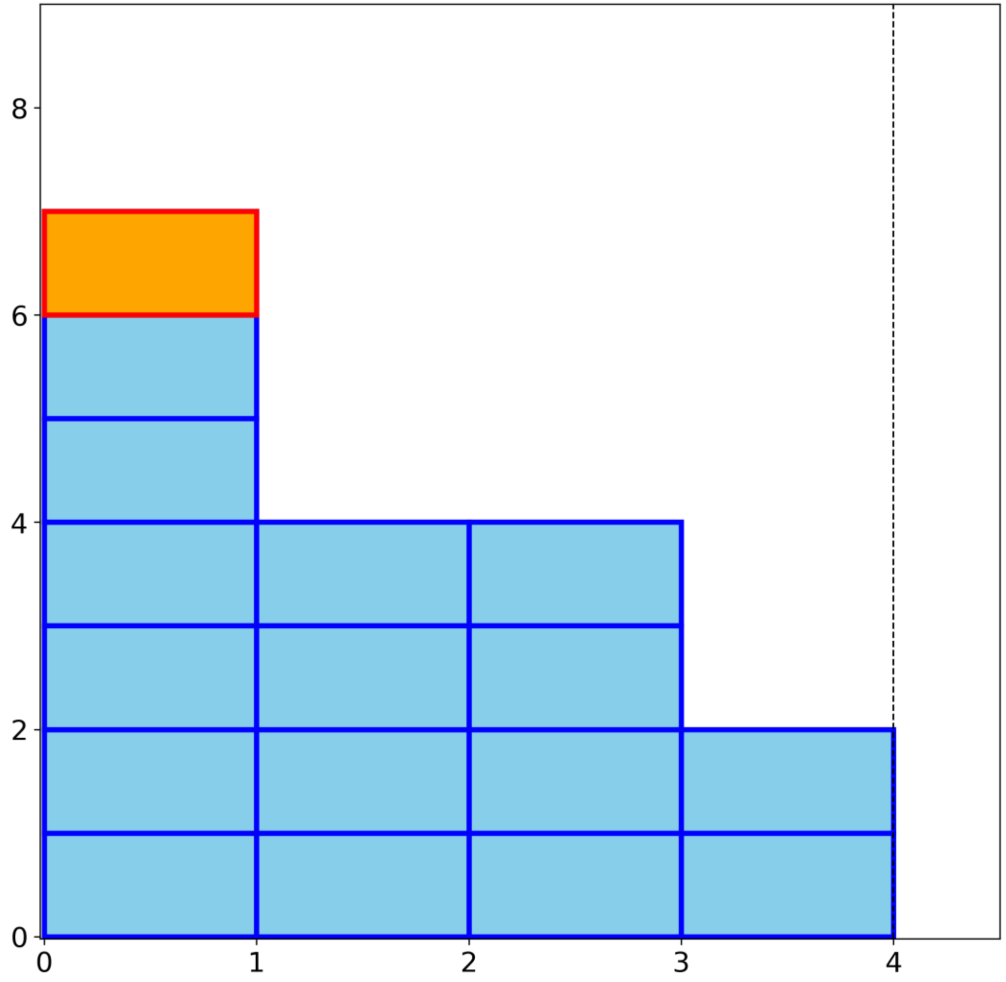

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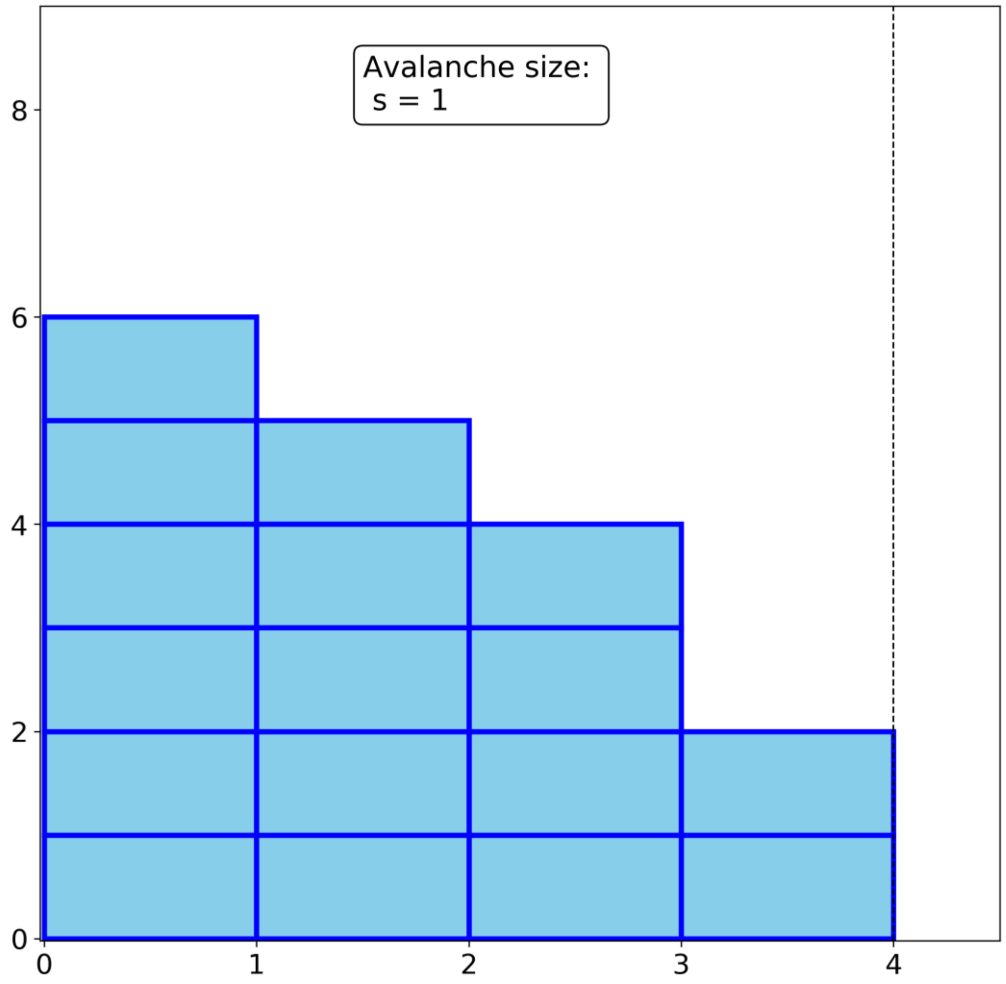

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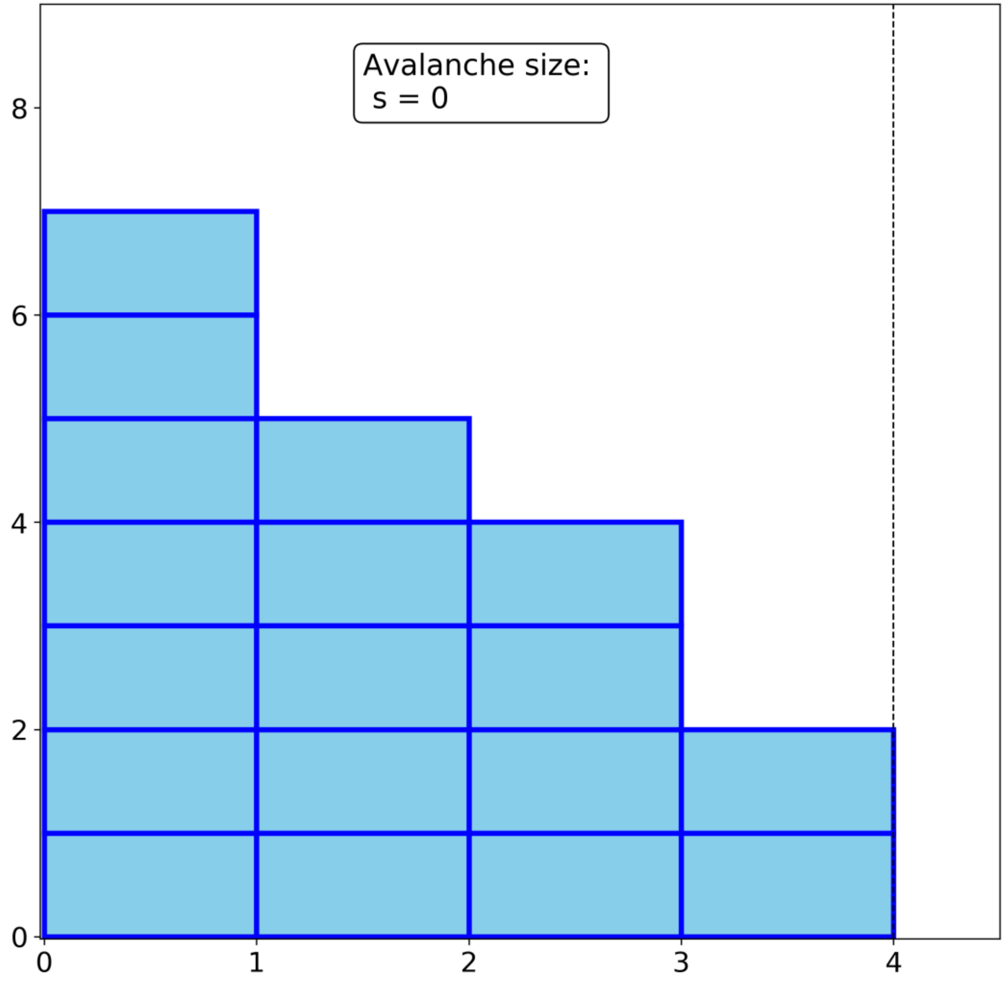

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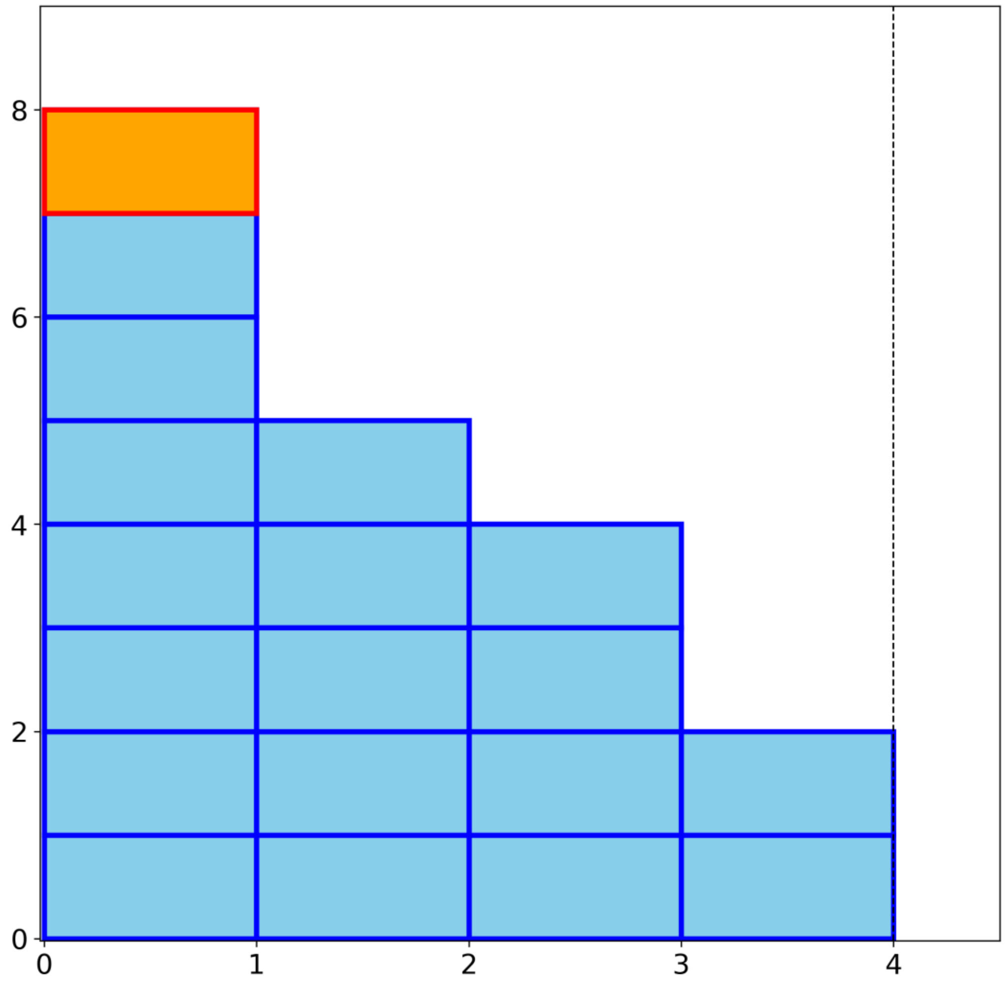

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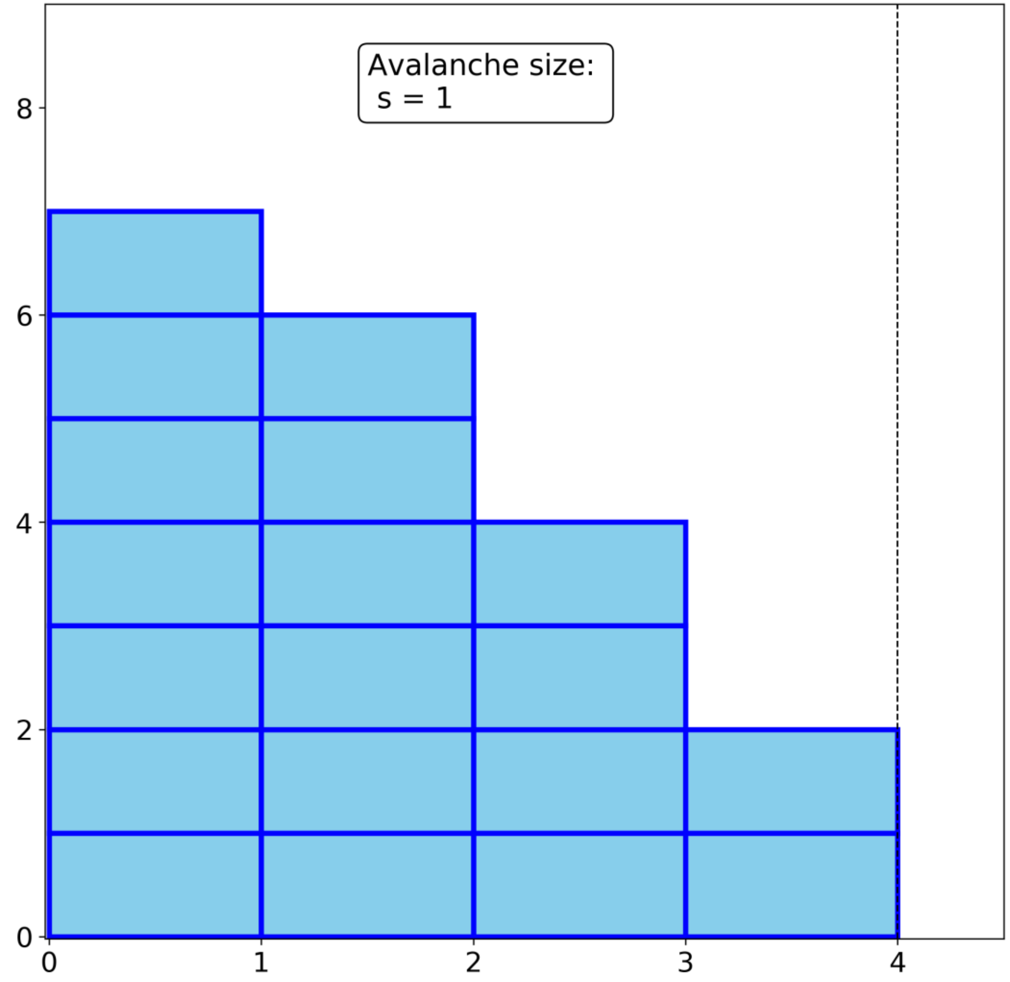

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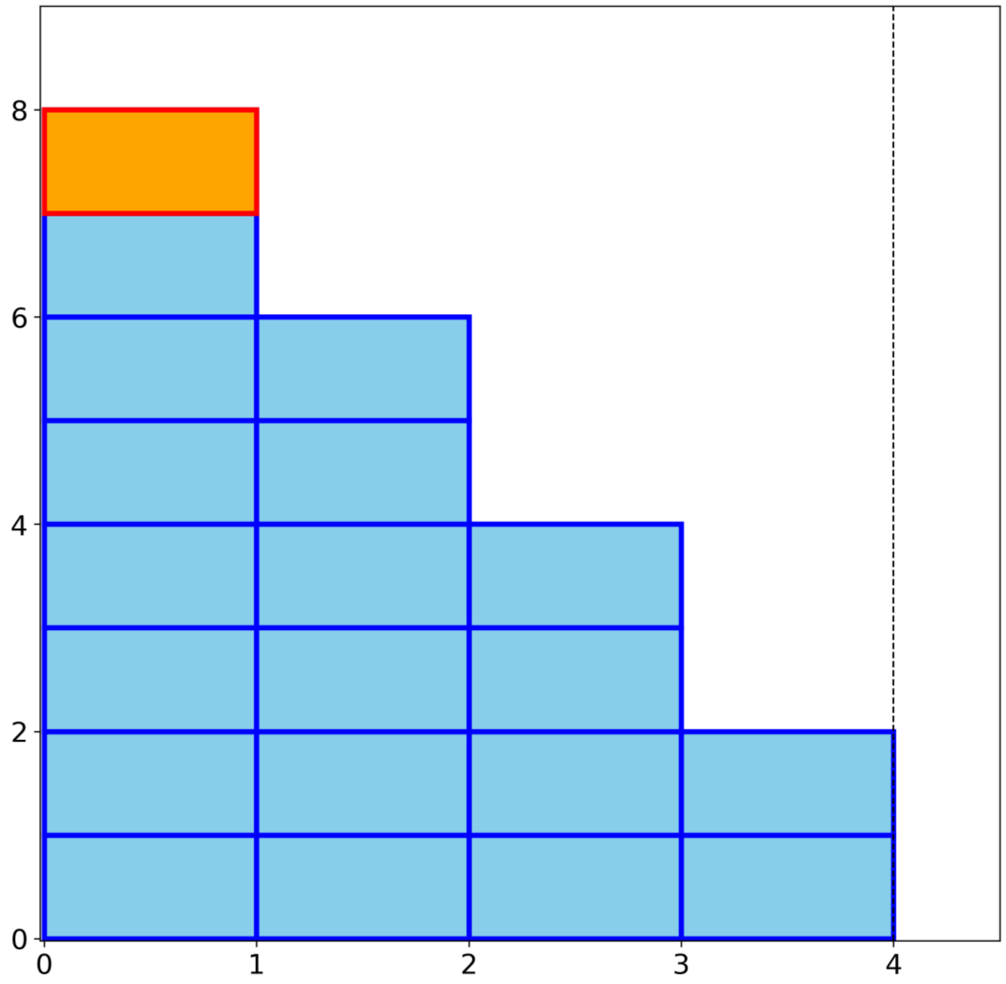

DEMONSTRATION – NON-TRIVIAL AVALANCHES

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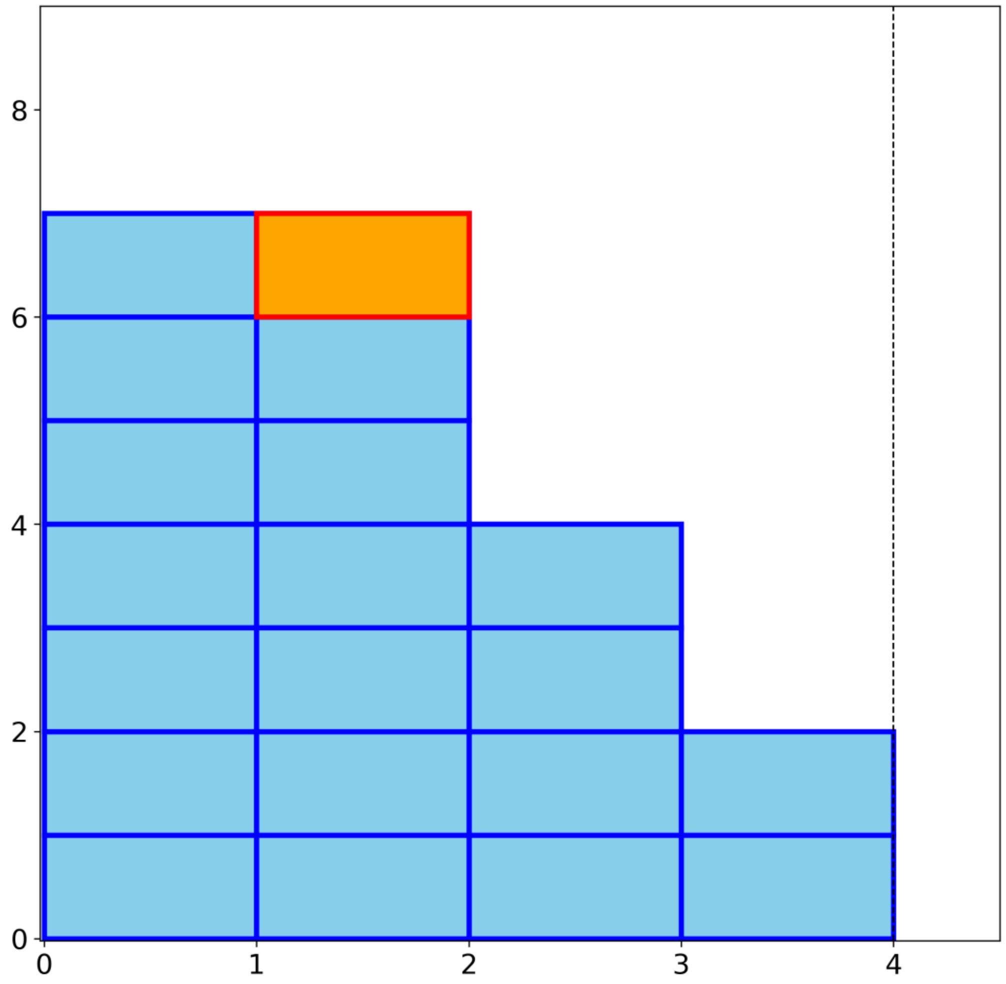

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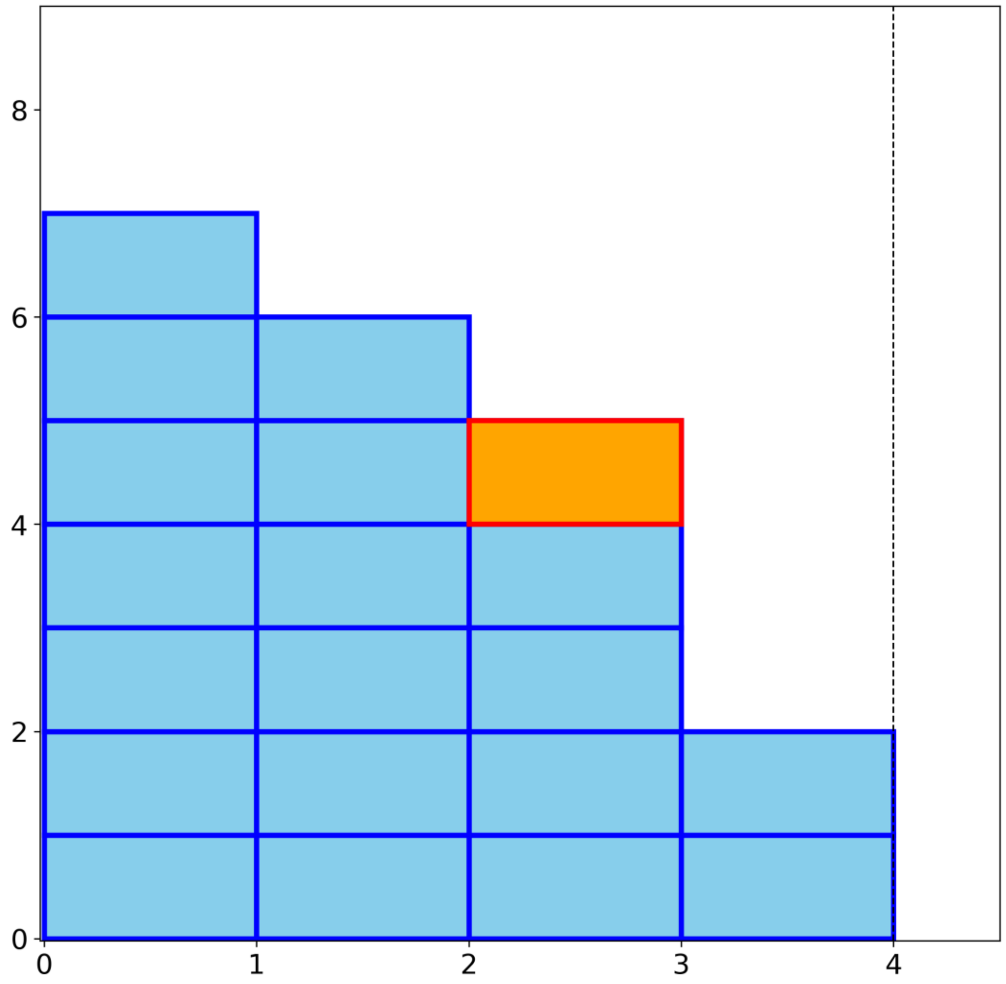

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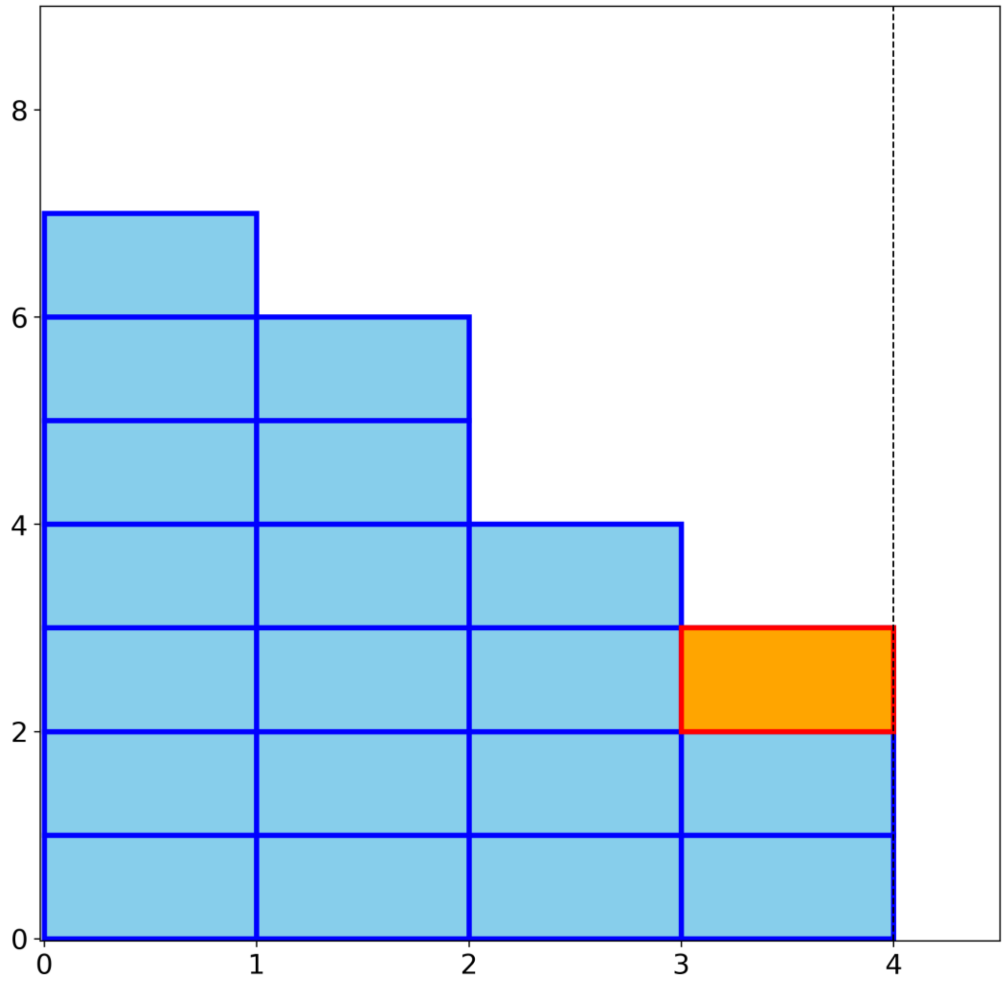

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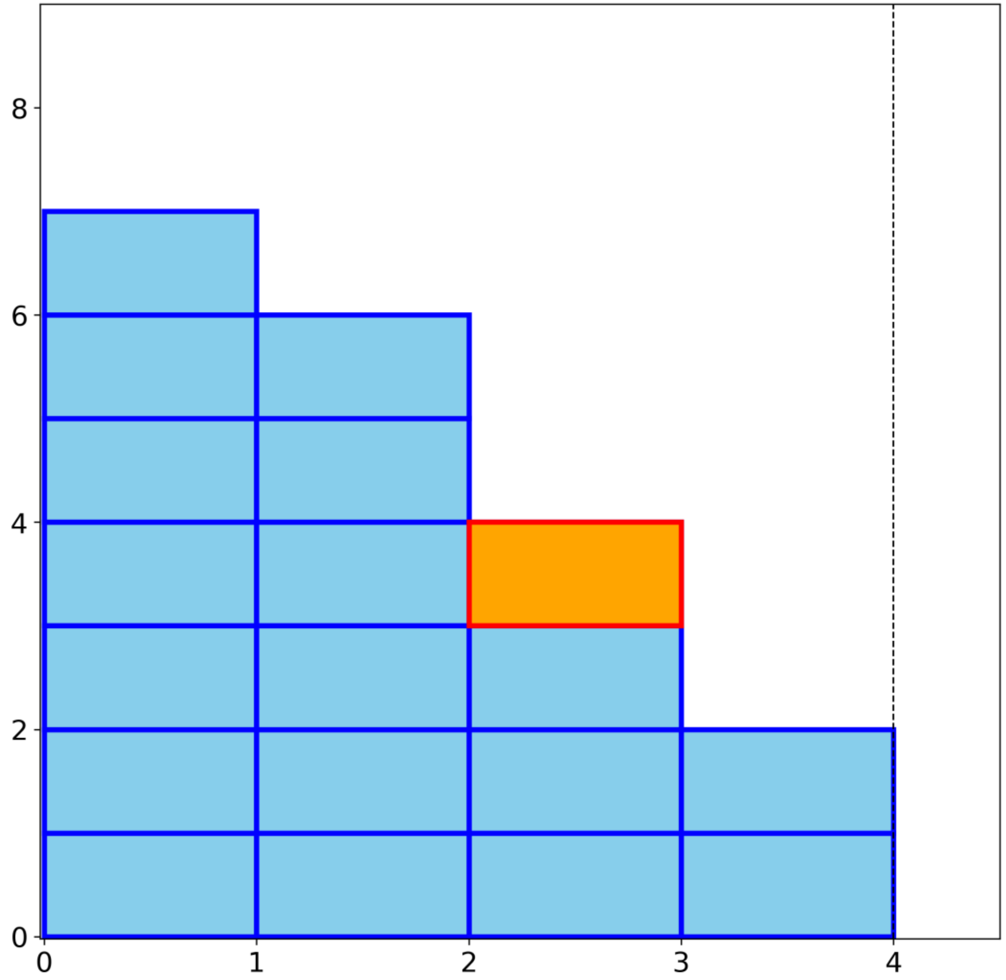

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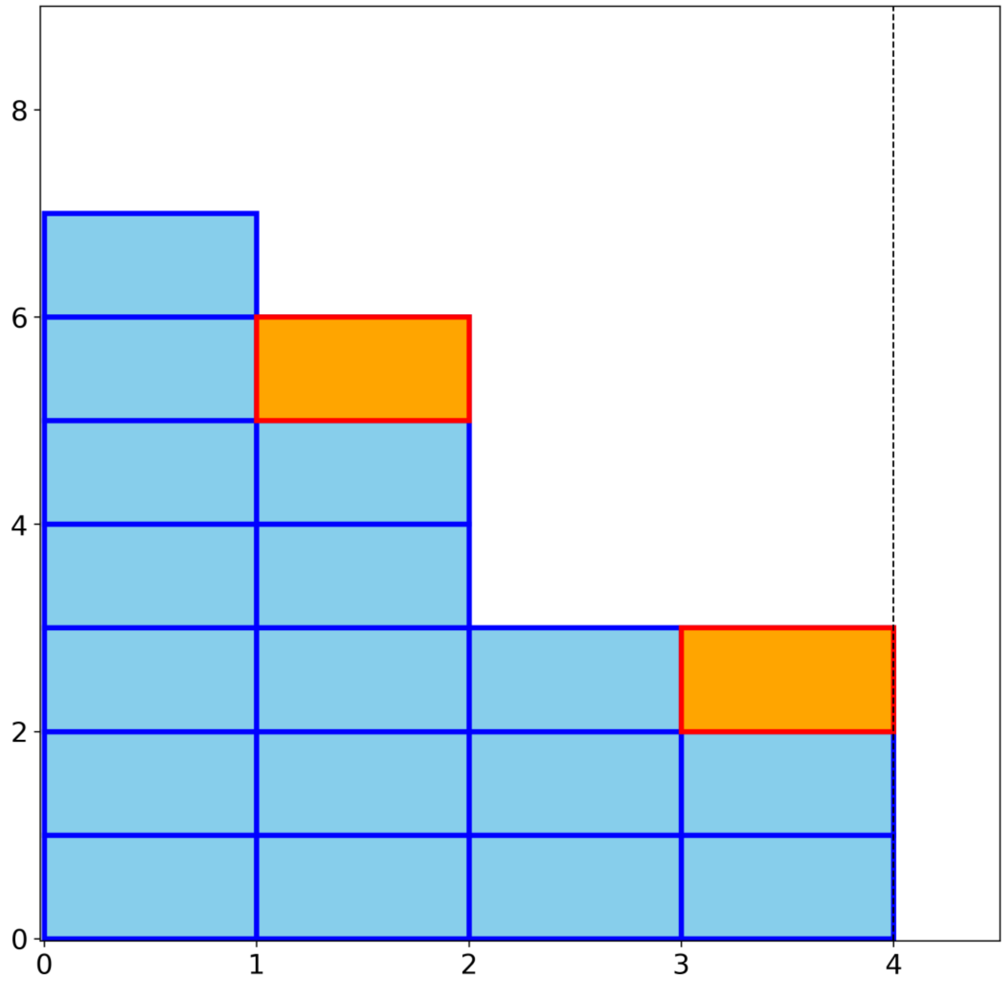

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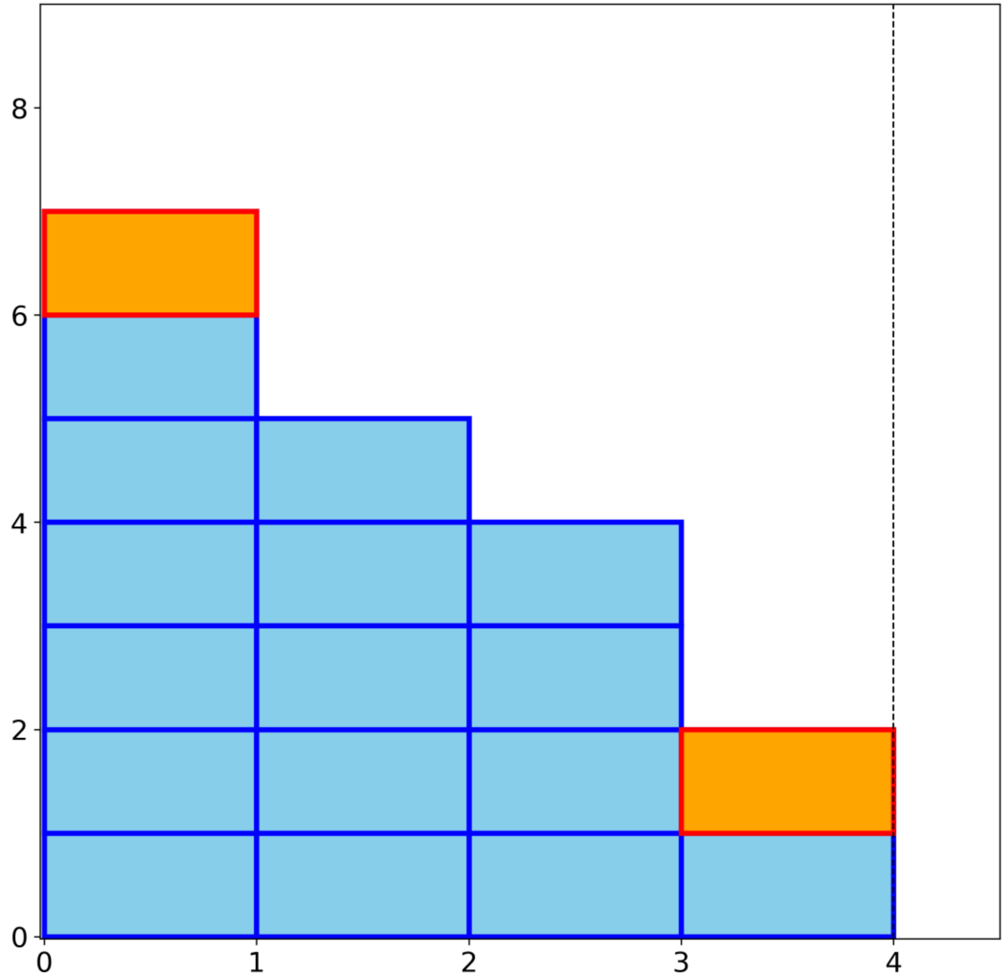

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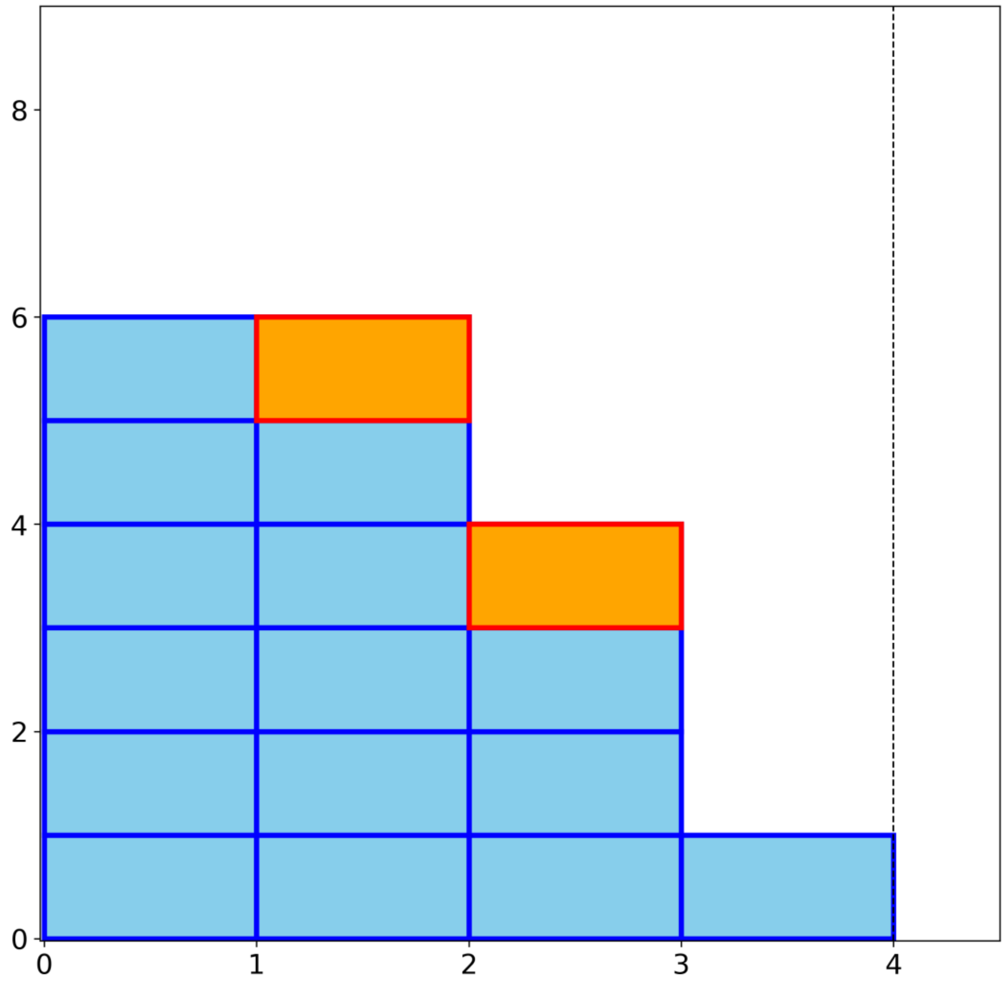

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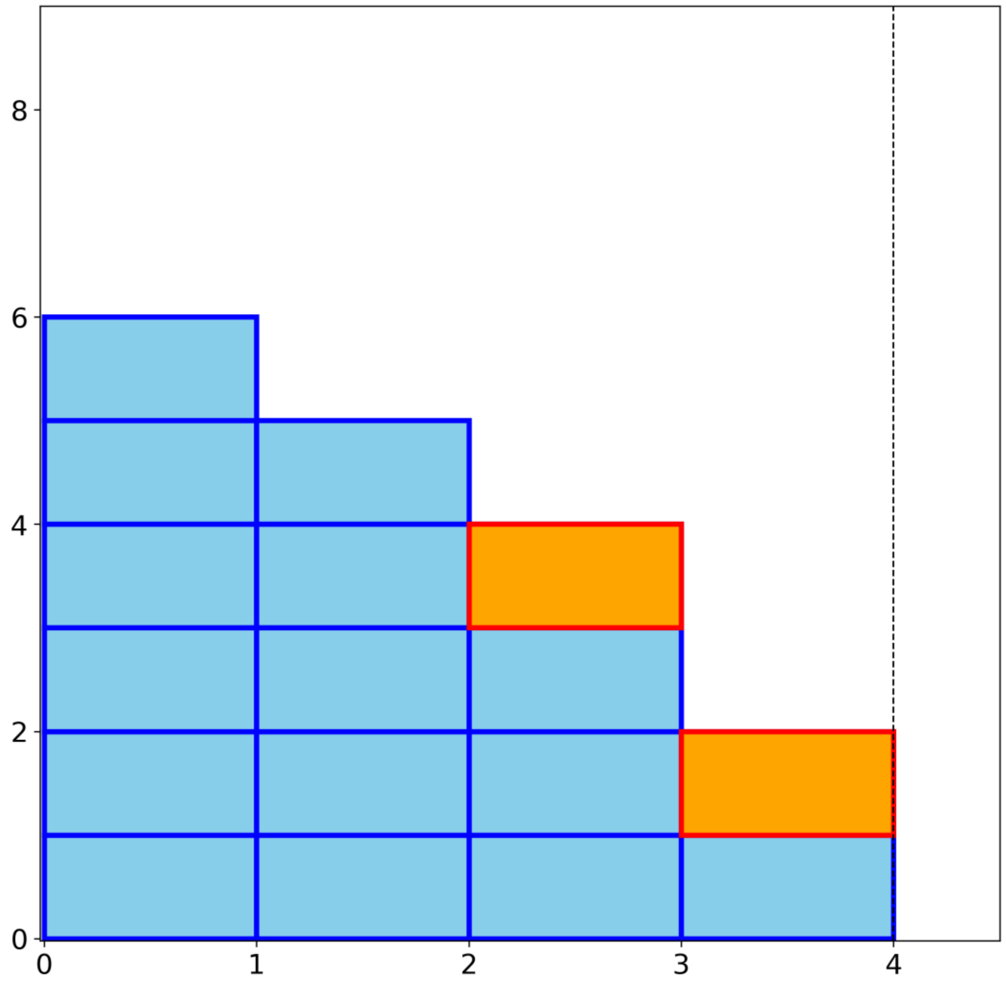

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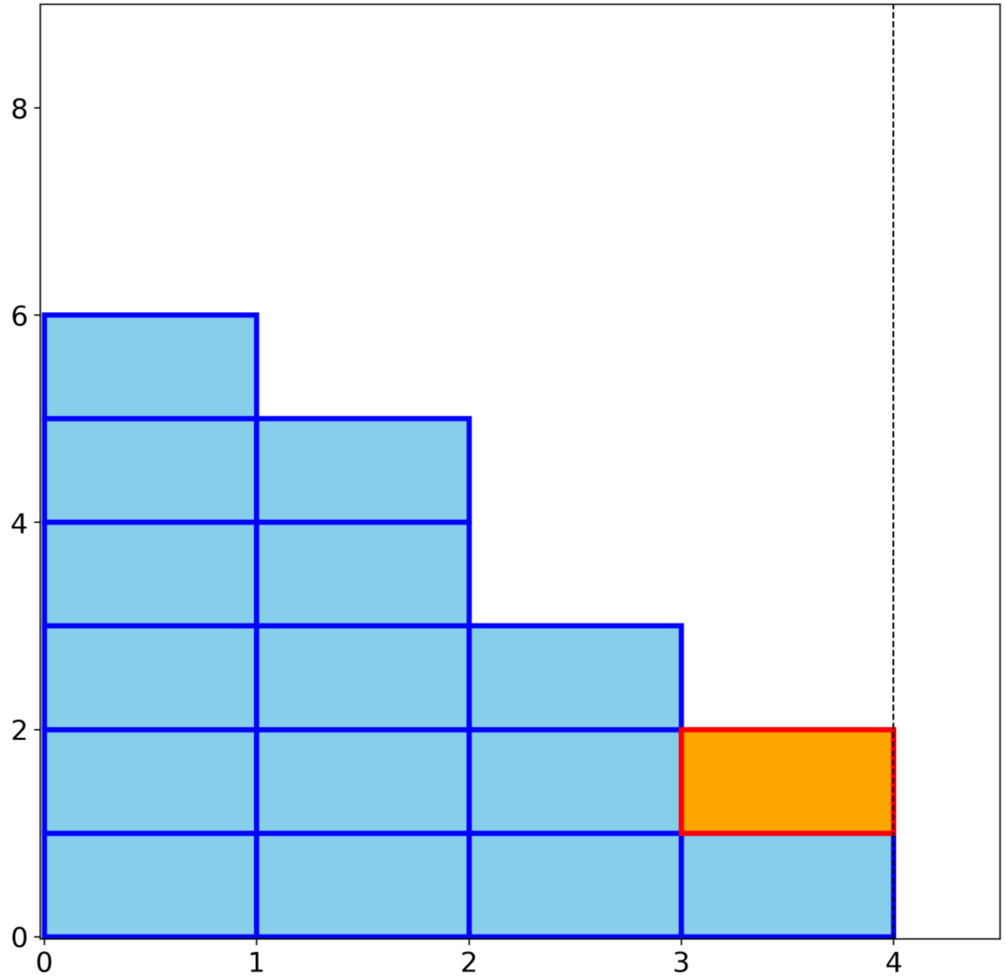

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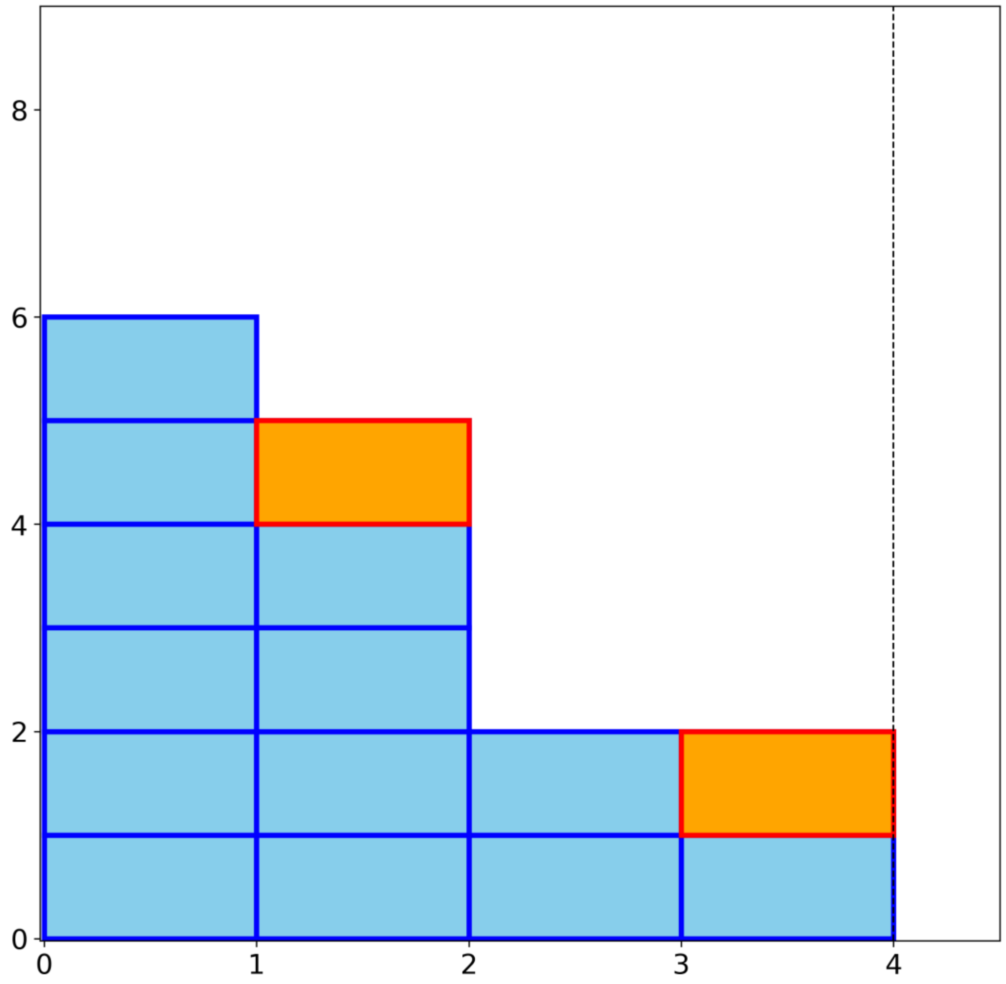

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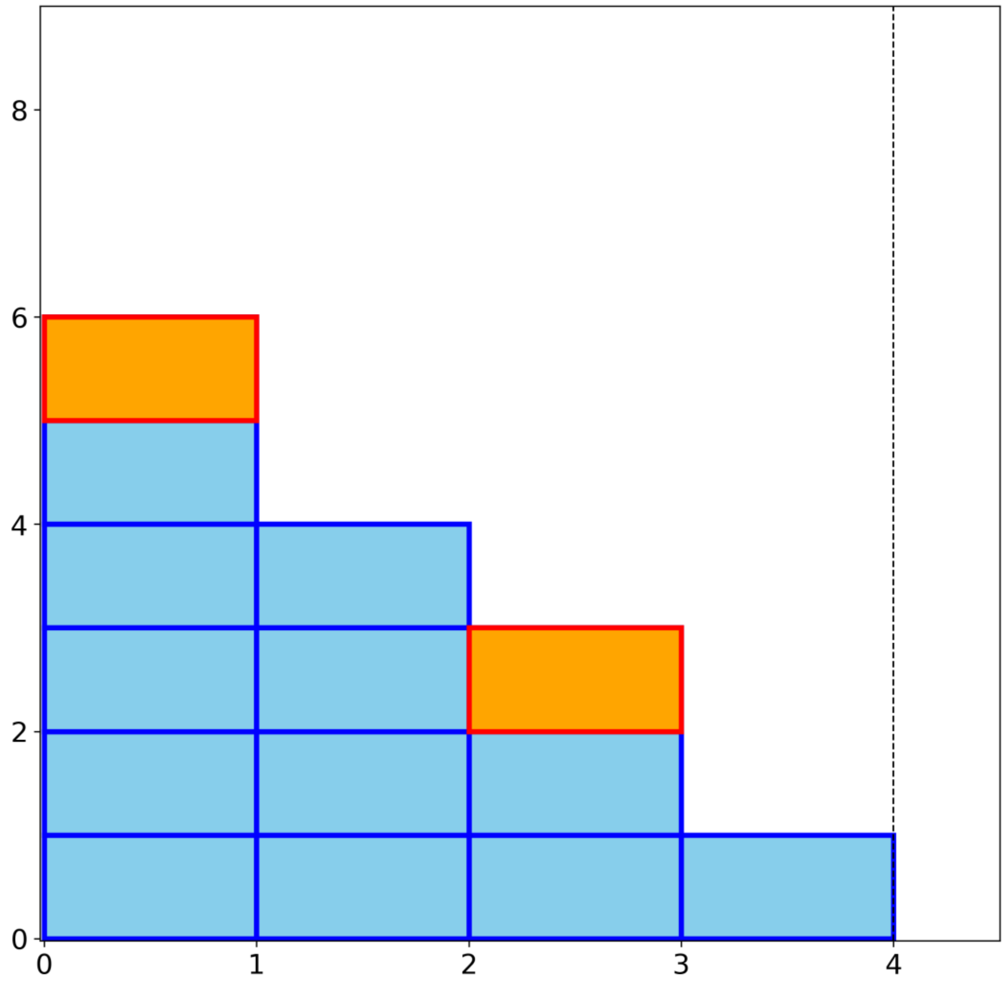

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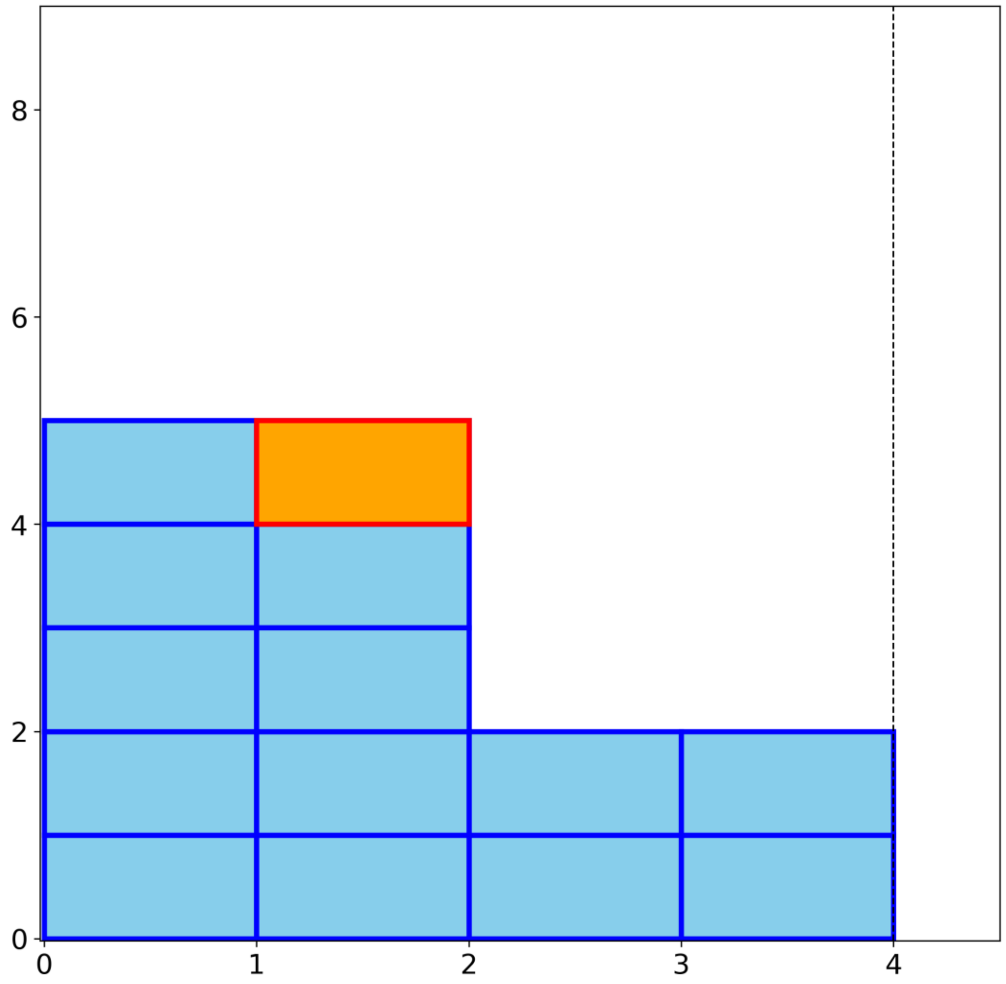

DEMONSTRATION – NON-TRIVIAL AVALANCHES

Now, choose critical slopes randomly with

- $P(z_{i,crit} = 1) = 1/2$
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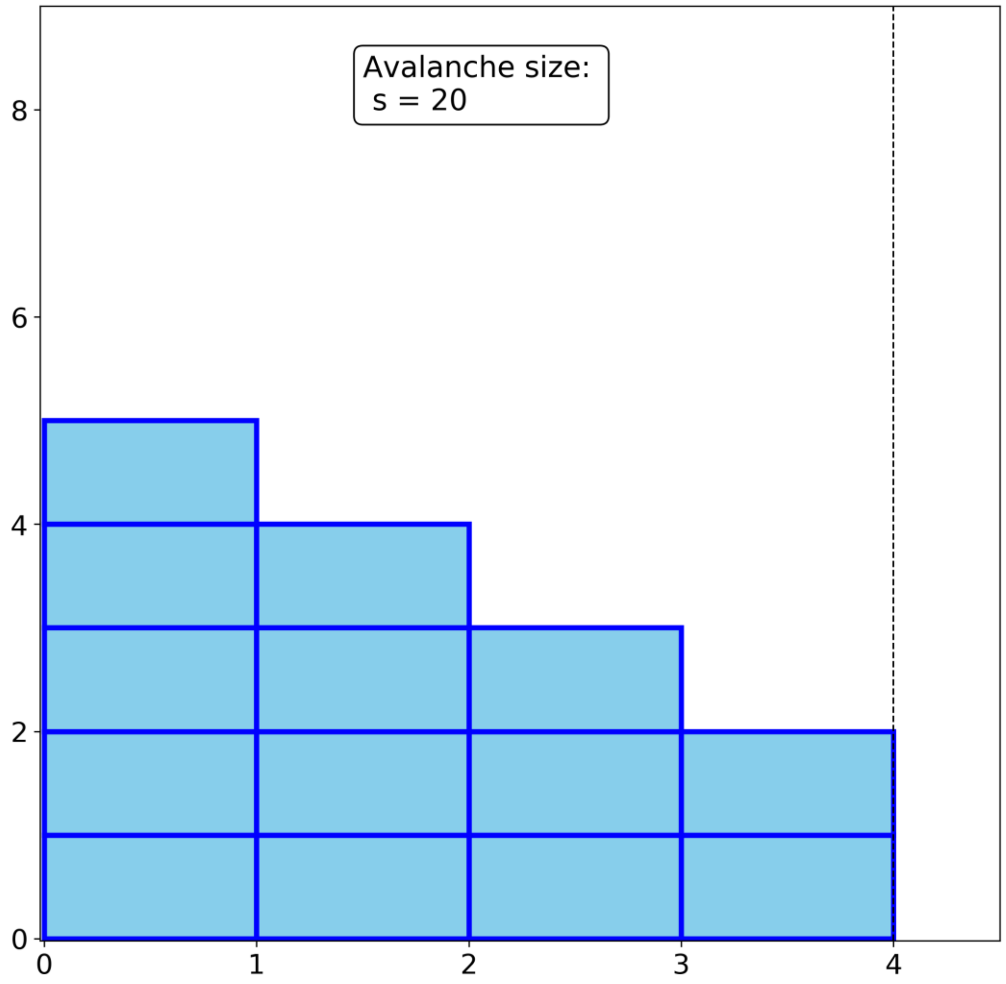
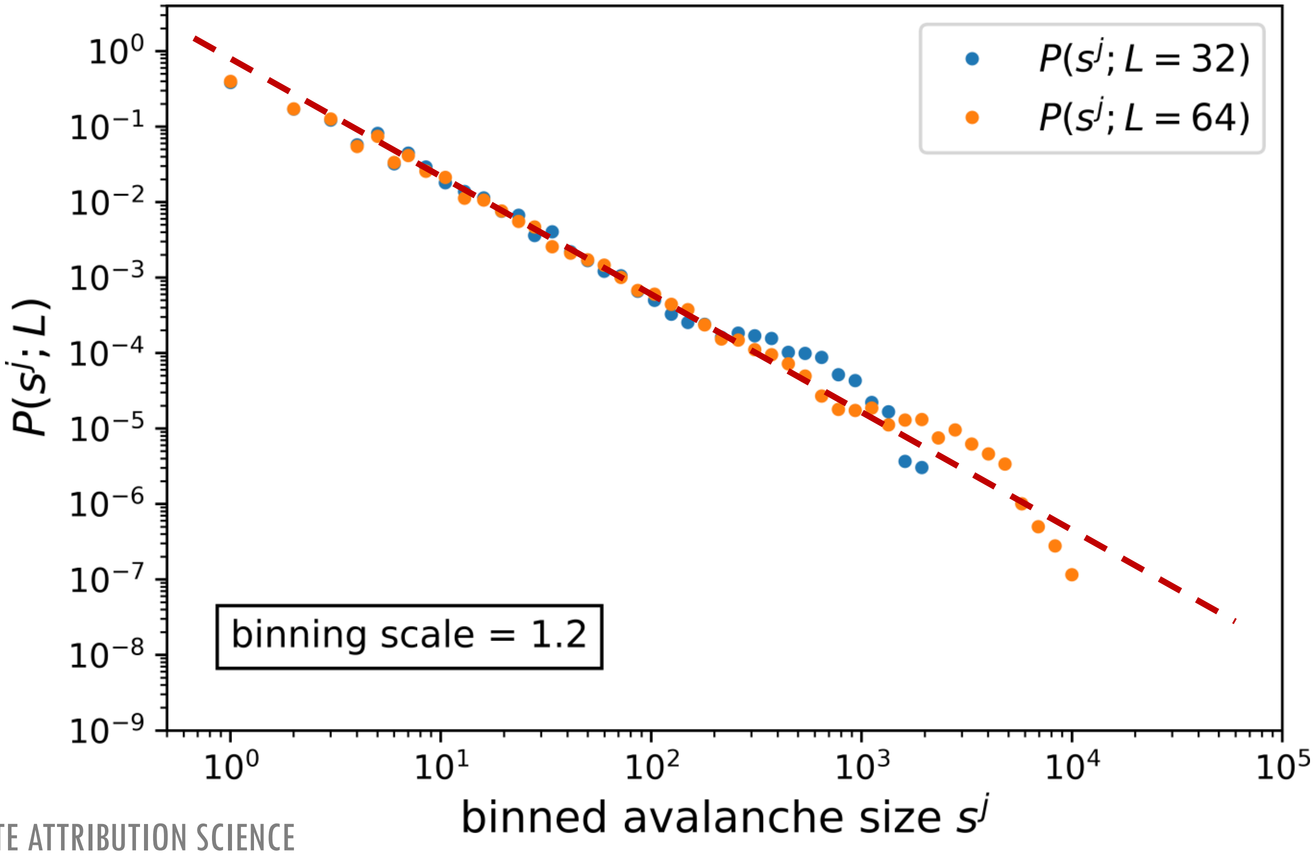
→ **Avalanches of very different sizes appear.**



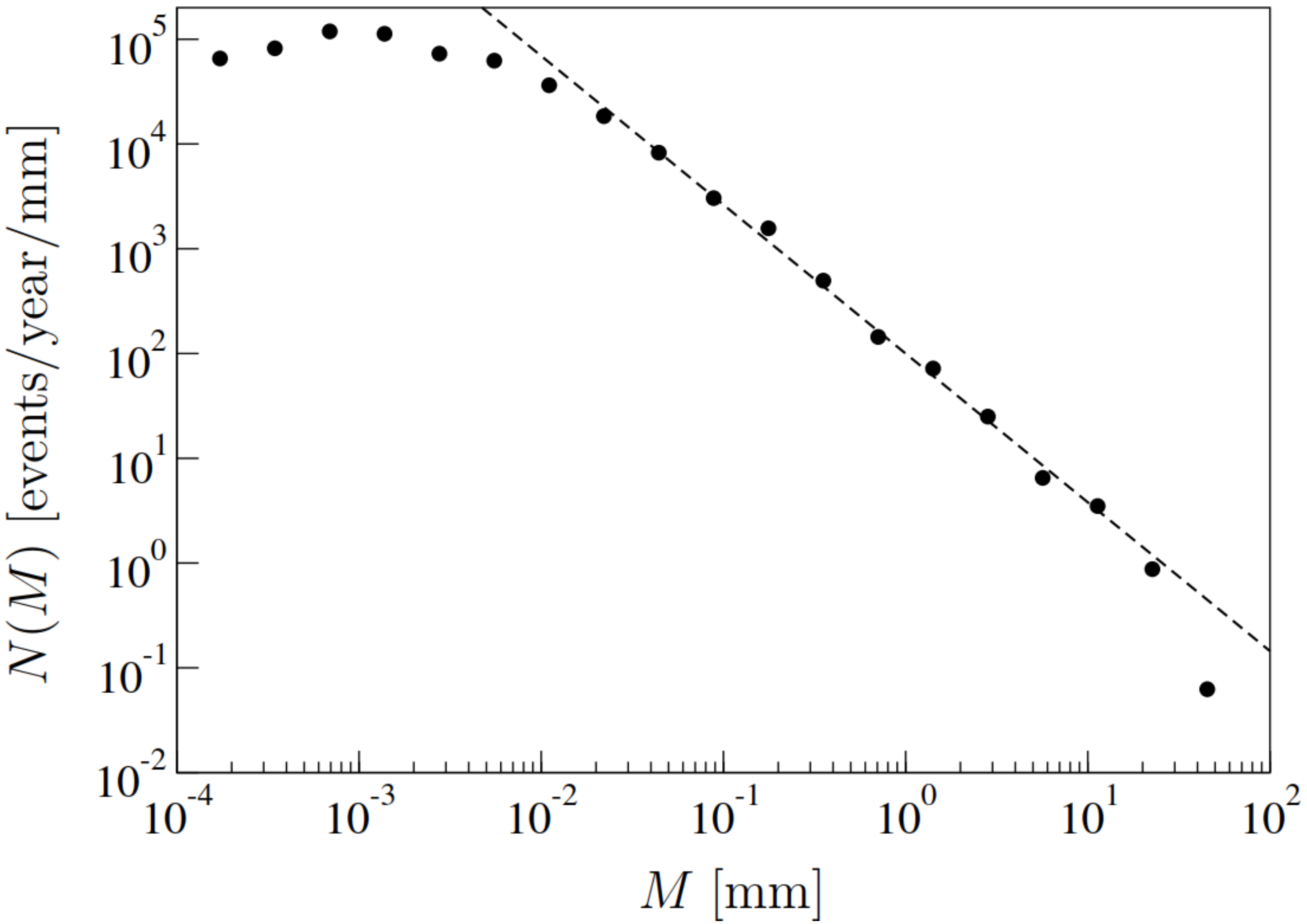
AVALANCHE SIZE PROBABILITY DISTRIBUTION

- **Avalanche size s** = total number of relaxations induced by a single grain



Based on 10000 avalanches.

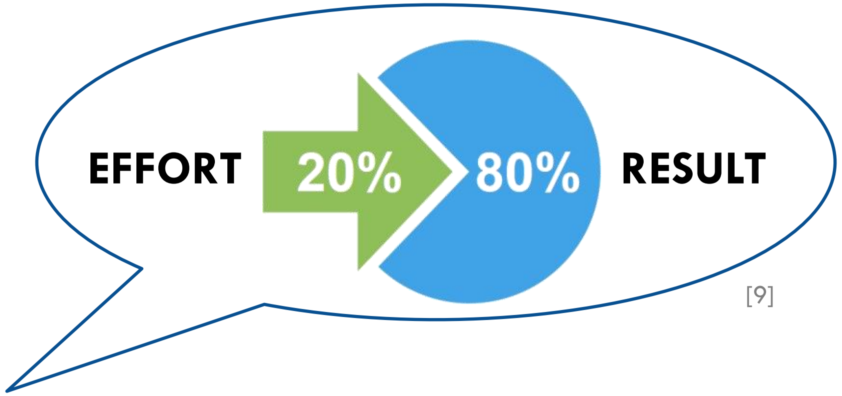
NUMBER OF RAINFALLS PLOTTED VS. EVENT SIZE



based on data from METEK covering the period 1.1.1999 to 1.7.1999 at the Baltic coast Zingst, Germany.

[Ref. A]

INTERPRETING THE METAPHOR



[9]

- Avalanche sizes follow a power law distributions (also **Pareto**-distribution)

  → they appear everywhere in nature and our everyday lives:

  - Earthquake magnitudes
  - finance
  - wealth distributions
  - networks like the WWW

- **Sand pile displays Self-Organised Criticality:**
  Smallest inputs (a single grain) produce avalanches of all orders of magnitude

→ Extreme events are unlikely but not unusual!

In other words:

In many systems, extreme events need no special "cause" or initialisation.
They are inherently part of the system.

MODIFYING THE SAND PILE MODEL

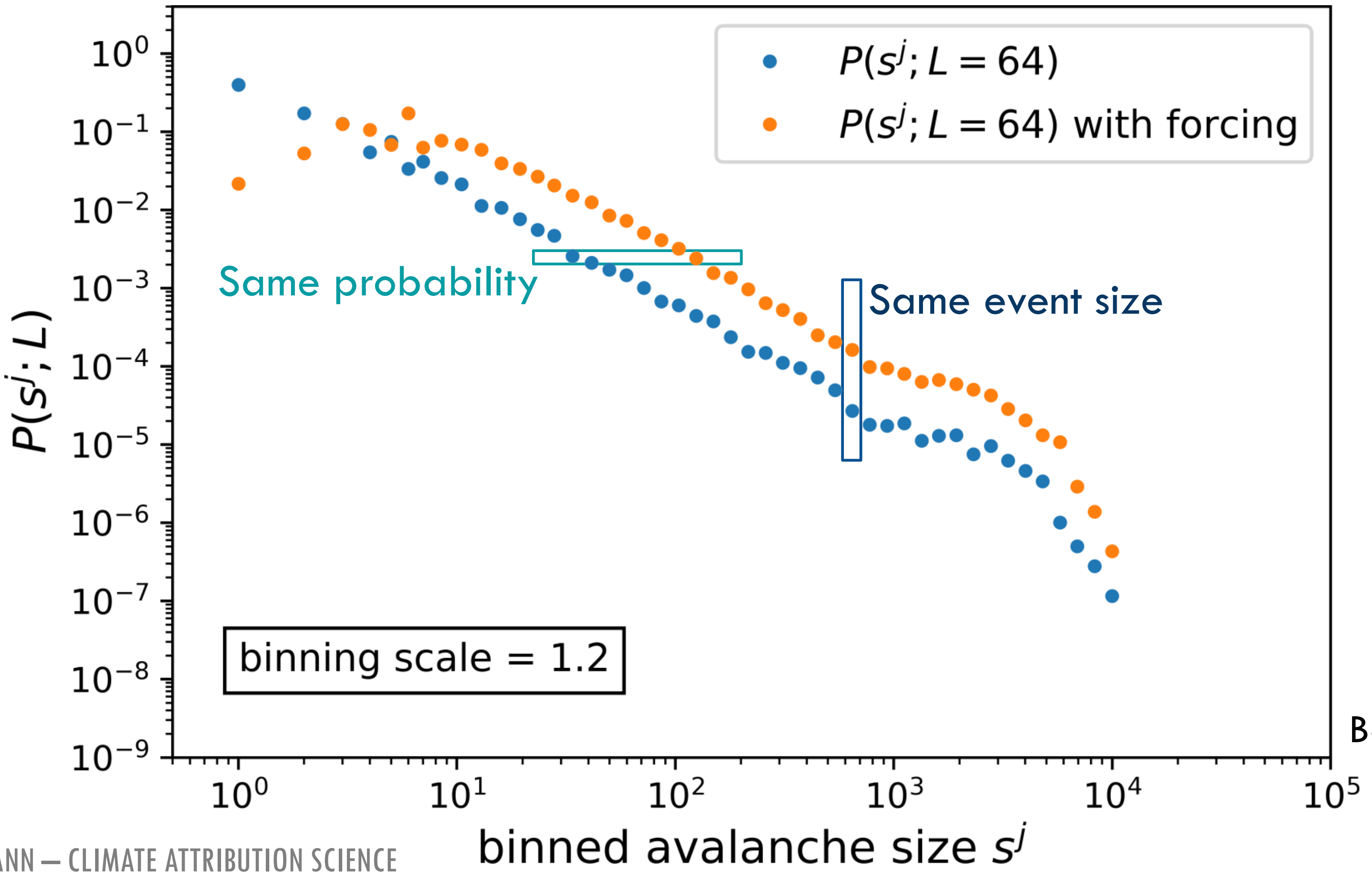
- This raises the following questions:
  → *Are weather extremes just natural variability?*
  → *Can we somehow influence the occurrence of extreme events in our sand pile toy model?*

- Note: One can make the sand pile model **more realistic** by
  - Building sand piles in two dimensions
  - Allowing for uneven (perhaps changing) ground

- However, in the case of a rain-fall model, one may **increase the evaporation**:

  → at each step add for instance 4 grains to the pile instead of 1.

MODIFYING THE SAND PILE MODEL



Based on 10000 avalanches.

OVERVIEW

1) What is climate attribution science?

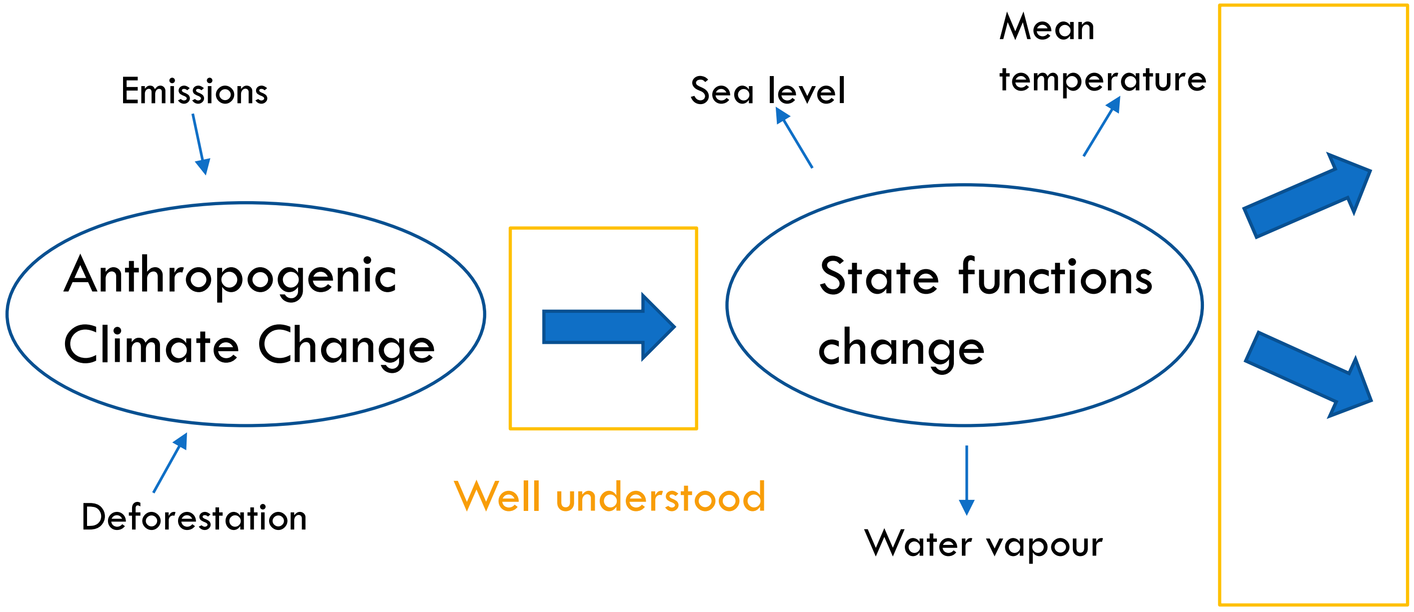
2) Weather as complex phenomenon

3) **How is it done in practice?**

4) Conclusion and Outlook

ATTRIBUTION OF EXTREME WEATHER
TWO APPROACHES

Did anthropogenic climate change make an extreme weather event more likely / more severe?



1.) Probabilistic approach

Risk & Characteristics of an **event type** (may) change

2.) Pathway approach:

Evolution of an **individual event** (may) change

Simulation and observation of weather extremes

1.) PROBABILISTIC APPROACH – PROCEDURE

Models are used to estimate the **probabilities** of occurrence of an event

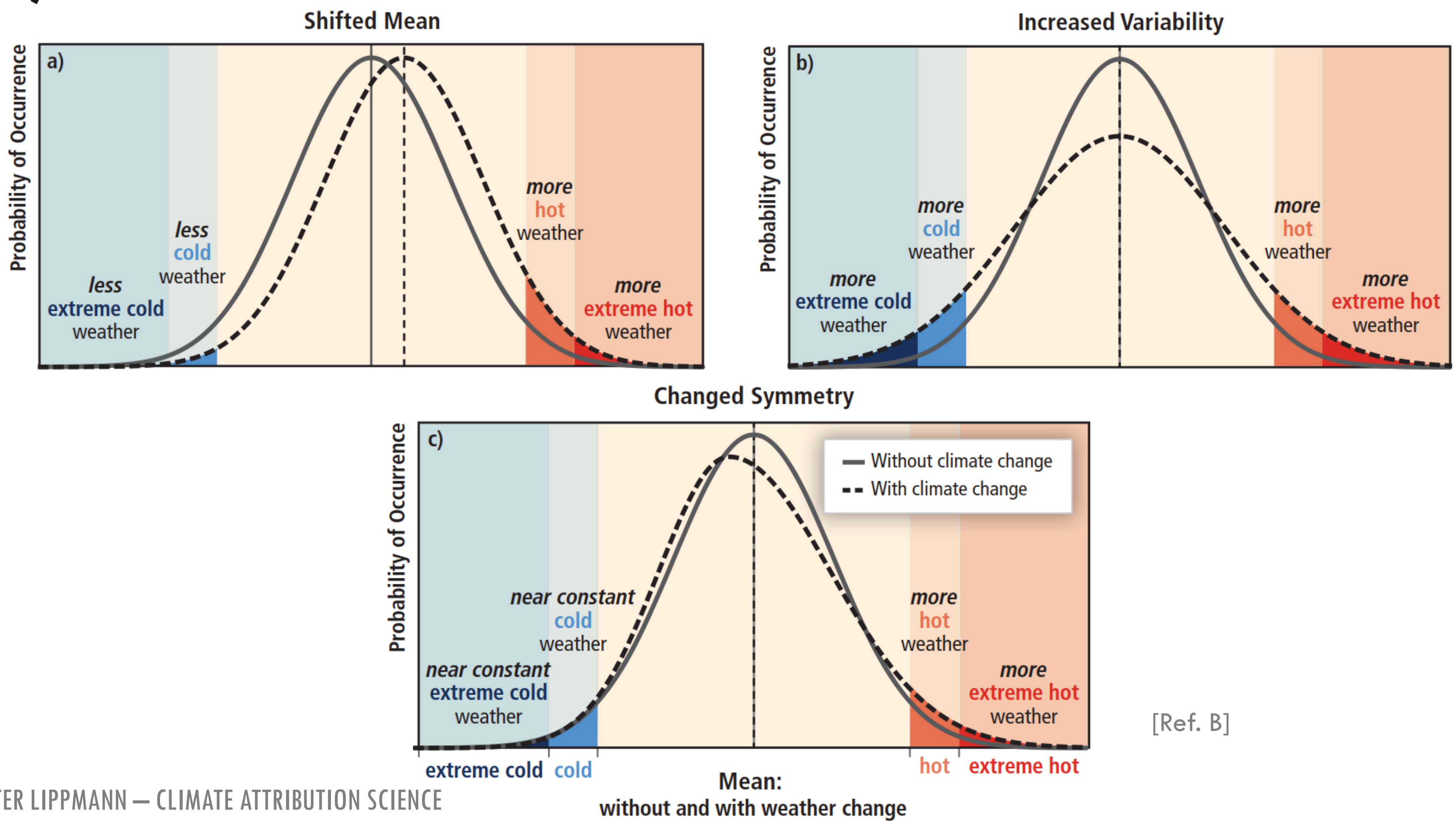
p_1 p_0

with human-caused climate changes (FACTUAL WORLD) VS. **without** these changes (COUNTERFACTUAL WORLD)

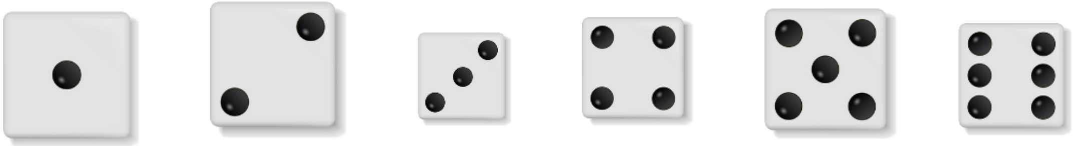
Examples: → simulate evolution of mean temperature in atmosphere **with** and **without** anthropogenic emissions

→ simulate occurrence of extreme rain events **with** and **without** additional water vapour in atmosphere

1.) PROBABILISTIC APPROACH – POSSIBLE SCENARIOS



[Ref. B]



[18]

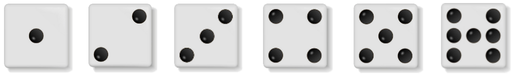
1.) PROBABILISTIC APPROACH – INTERPRETATION

Given $\boldsymbol{p_1}$ and $\boldsymbol{p_0}$. What are their interpretation in terms of attribution science?

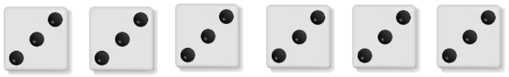
- Two commonly used measures:

Risk Ratio $\boxed{RR = \frac{p_1}{p_0}}$ Fraction of Attributable Risk $\boxed{FAR = 1 - \frac{p_0}{p_1}}$ [Ref. C]

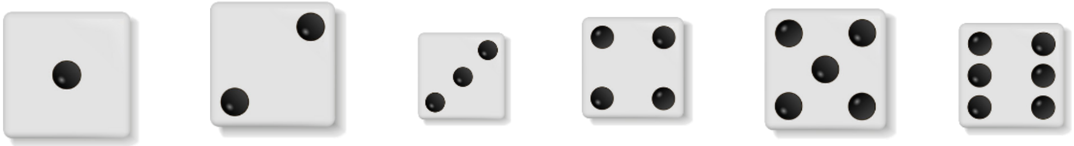
- Example: *Did we only experience a specific dice outcome only because one has manipulated it?*

A) Manipulation:  → Outcome:  .

Necessary cause. (**Not present in the case of weather,** since events were possible all along)

B) Manipulation:  → Outcome:  .

Sufficient cause. (**Not present in the case of weather,** since no deterministic causation)

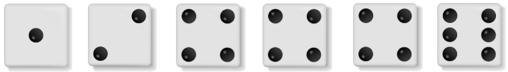

[18]

1.) PROBABILISTIC APPROACH – INTERPRETATION

Risk Ratio $\boxed{RR = \frac{p_1}{p_0}}$

Fraction of Attributable Risk $\boxed{FAR = 1 - \frac{p_0}{p_1}}$

- Example: *Did we only experience a specific dice outcome only because one has manipulated it?*

C) For us relevant manipulation:  → Outcome:  .

↳ $$FAR = 1 - \frac{1/6}{3/6} = \frac{2}{3}$$

"Out of 3 events that happened in the factual world 2 would not have happened in the counterfactual one."

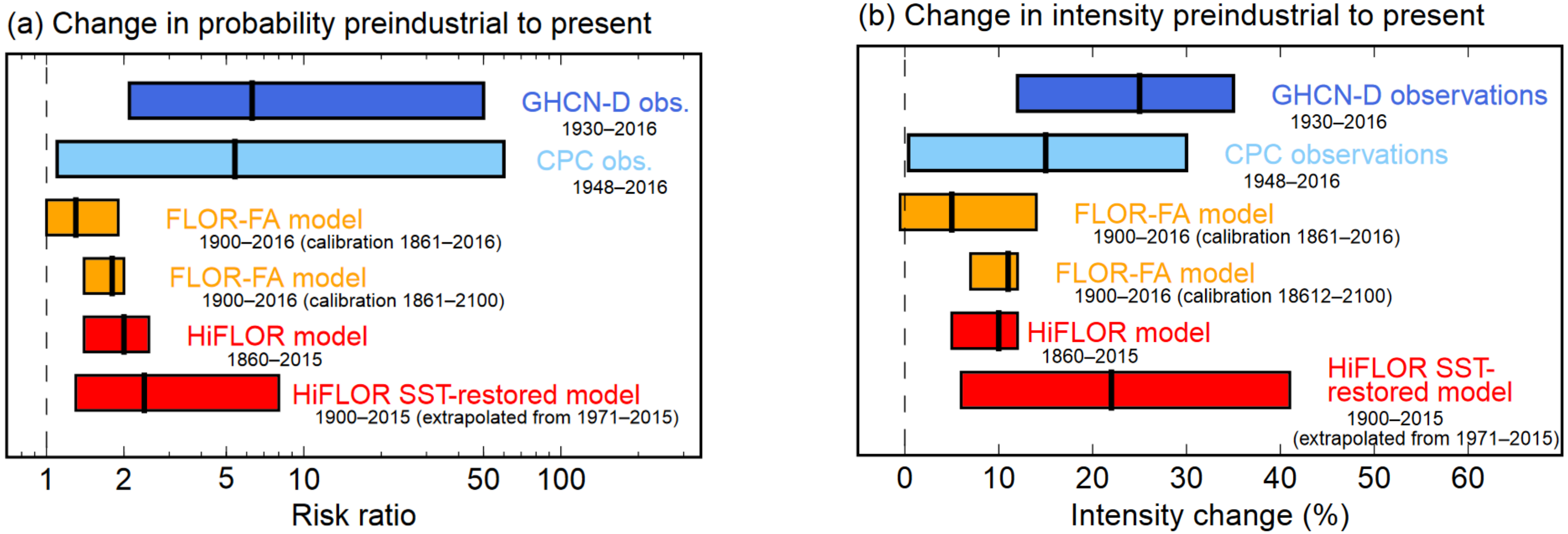
↳ $$RR = \frac{3/6}{1/6} = 3$$

"Manipulating the dice increased the risk of getting a 4 by a factor of 3."

1.) PROBABILISTIC APPROACH – AN EXAMPLE

[10]

- TASK: Attribution of the flood-inducing extreme precipitation in south Louisiana in August 2016



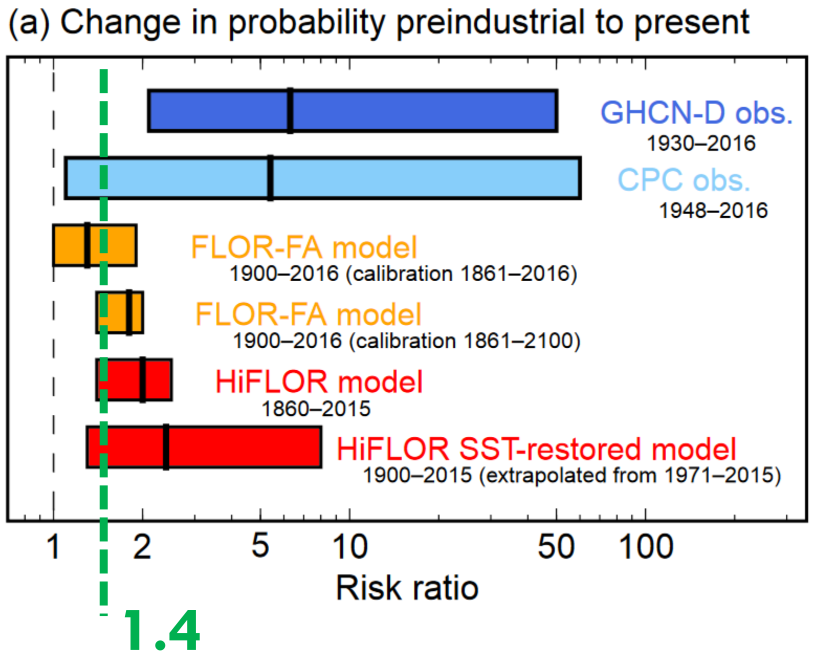
[Ref. D]

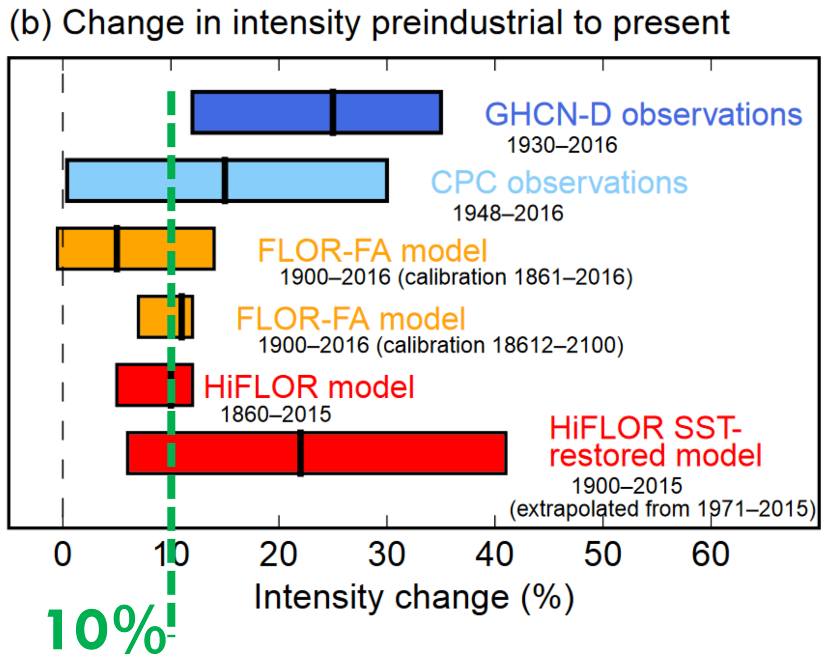
- repeat simulation with small changes in the initial conditions to estimate **uncertainties and sensitivities**
- combine many models and different studies to ensure the obtained result is not particularly sensitive to the **definition of an event**

1.) PROBABILISTIC APPROACH – AN EXAMPLE

[10]

- TASK: Attribution of the flood-inducing extreme precipitation in south Louisiana in August 2016





[Ref. D]

"In the most accurate analyses, the regional probability of 3-day extreme precipitation increases by more than a factor of 1.4 due to anthropogenic climate change." [Ref. D]

2.) PATHWAY APPROACH – PROCEDURE

- NOW: Attribution of an **individual weather event**
- Schematic pathway of a hurricane:

 …  …  …  … 

… 

too chaotic to simulate reliably

[11-16]

- **Condition the simulation** on location at which storm formed, wind directions, atmospheric pressure, …
- Then ask: How would the event have played out in a counterfactual world?
  - How might its intensity have changed because of changes in SST or atmospheric humidity along its path?
  - If the hurricane made landfall, how was the coastal flooding increased by long-term sea level rise?

2.) PATHWAY APPROACH – AN EXAMPLE

- Attribution study from 2013: *Simulations of Hurricane Katrina (2005) under sea level and climate conditions for 1900*

→ Compared actual impacts of Hurricane Katrina in New Orleans
VS. impacts of similar hypothetical hurricane occurring around 1900.

- Result:

> "Surge simulations suggest that flood elevations would have been **15 to 60 % lower** around 1900 than the conditions observed in 2005.
> This drastic change suggests that **significantly more flood damage** occurred in 2005 than would have occurred if sea level and climate conditions had been like those around 1900." [Ref. E]

OVERVIEW

1) What is climate attribution science?
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4) **Conclusion and Outlook**

CONCLUDING REMARKS

- Tough question: Is anthropogenic climate change to some extend responsible for extreme weather events?
- Climate Change does and will impact people, ecosystems and economy.
  To us it becomes concrete in extreme weather events.
- Fundamental Problem of Causal Inference: There is only one world!
  Key Challenge: How does one obtain the counterfactuals?

→ **SIMULATIONS** turn out to be extremely powerful!

→ Understanding the **SCIENCE** and mechanisms behind an event is thus the bread and butter of all attribution studies.

THANK YOU FOR YOUR ATTENTION!

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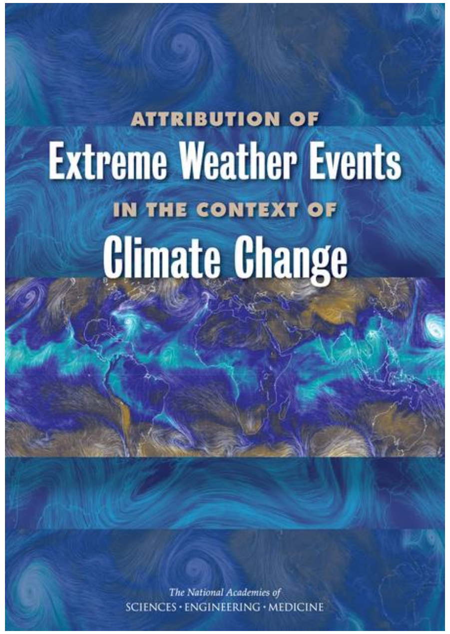

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