A microscopic concavity property and $t^{1/3}$ scaling of current fluctuations in particle systems

Joint with
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Technion, January 20-22, 2009.

The models

- Asymmetric simple exclusion process
- Zero range
- Bricklayers

Hydrodynamics

- Characteristics

Tool: the second class particle

- Single
- Many second class particles

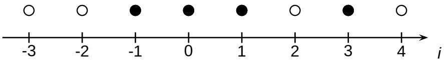
Results

- Normal fluctuations
- Abnormal fluctuations

Proof

- Upper bound
- Lower bound
- Microscopic concavity/convexity

Asymmetric simple exclusion



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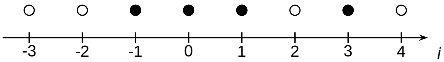

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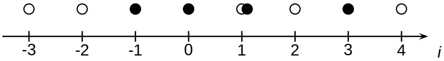

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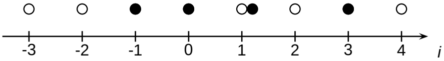

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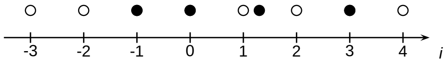

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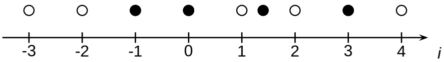

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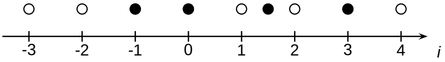

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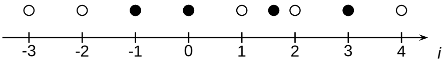

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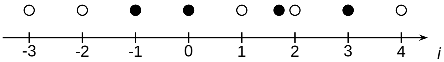

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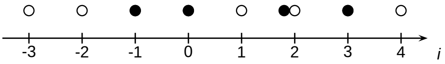

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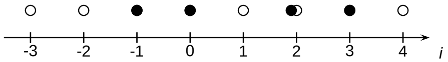

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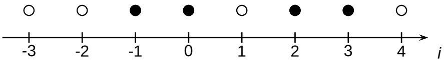

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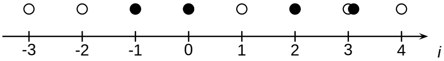

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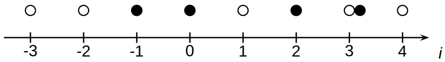

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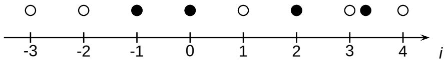

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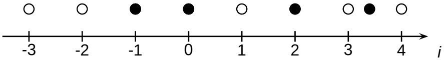

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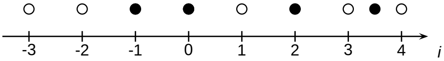

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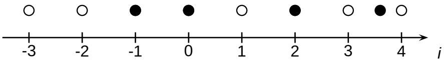

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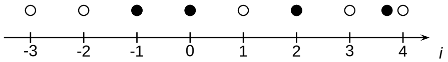

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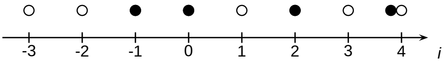

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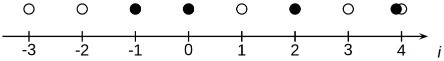

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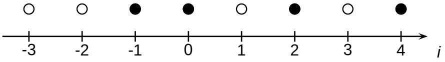

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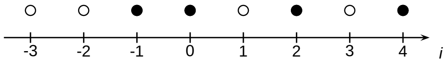

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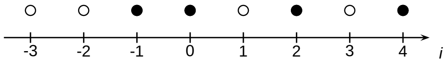

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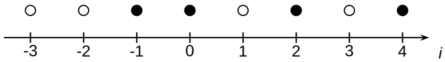

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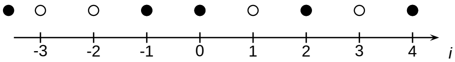

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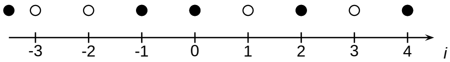

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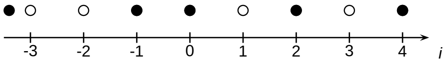

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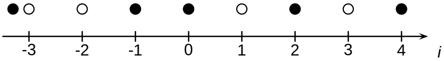

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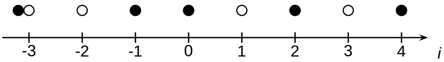

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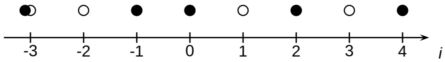

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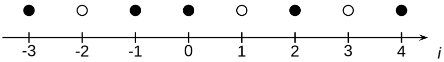

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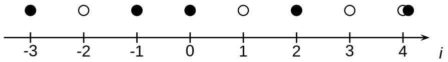

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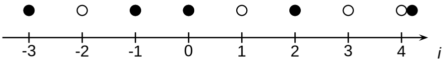

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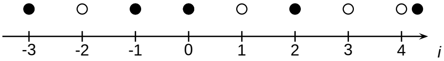

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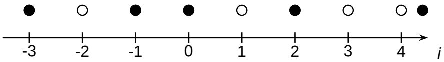

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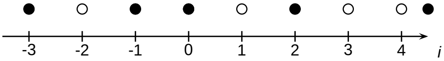

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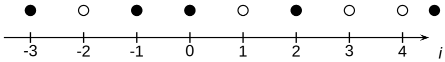

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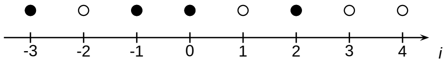

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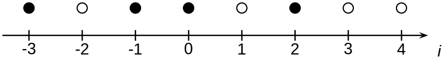

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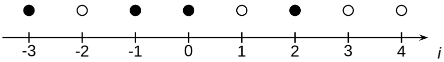

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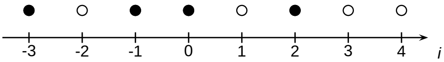

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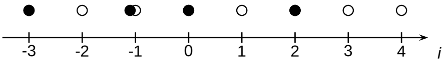

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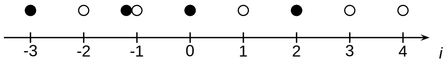

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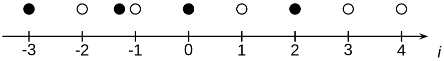

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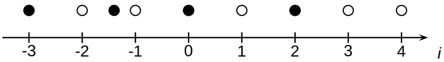

Bernoulli(ϱ) distribution; $\omega_i = 0$ or 1.

Particles try to jump

to the right with rate p,
to the left with rate $q = 1 - p < p$.

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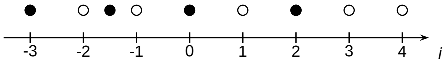

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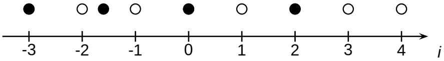

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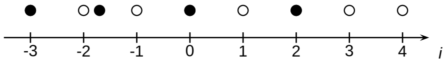

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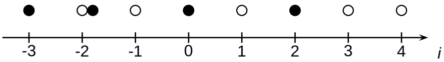

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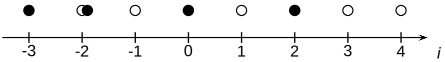

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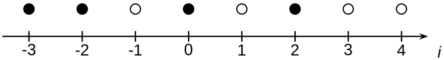

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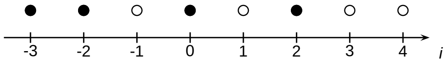

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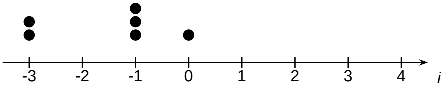
The Bernoulli(ϱ) distribution is time-stationary for any $(0 \le \varrho \le 1)$. Any translation-invariant stationary distribution is a mixture of Bernoullis.

The asymmetric zero range process



Poisson-type distribution; $\omega_i \in \mathbb{Z}^+$.

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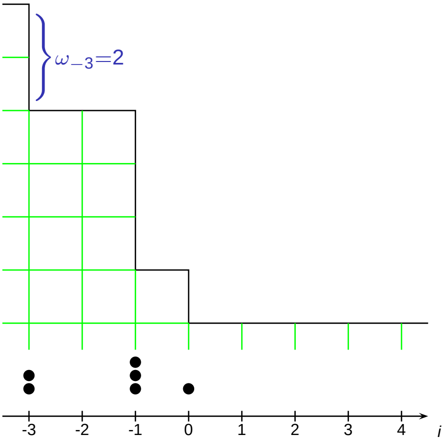

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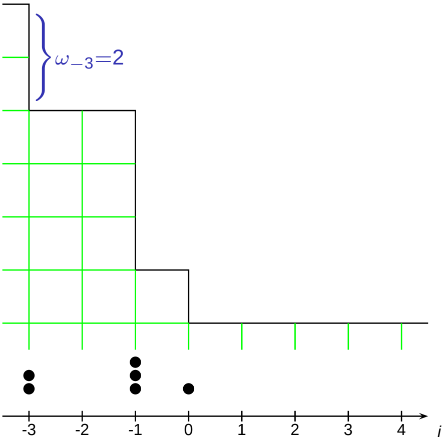

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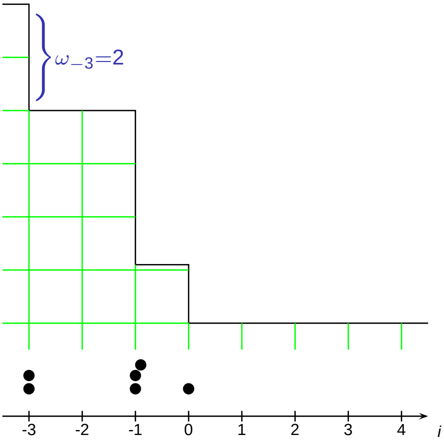

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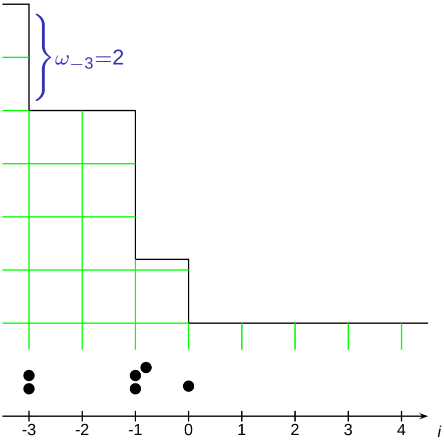

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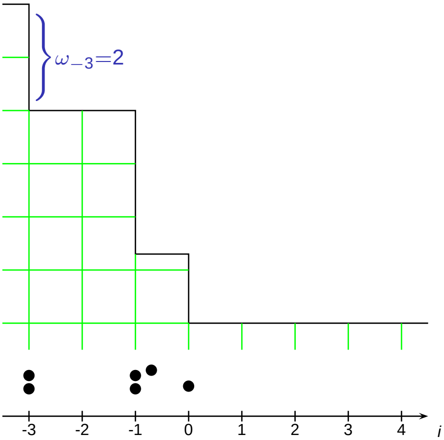

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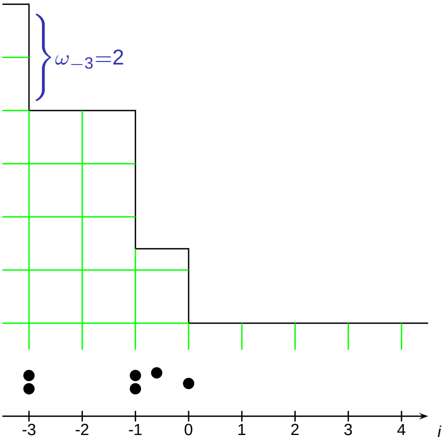

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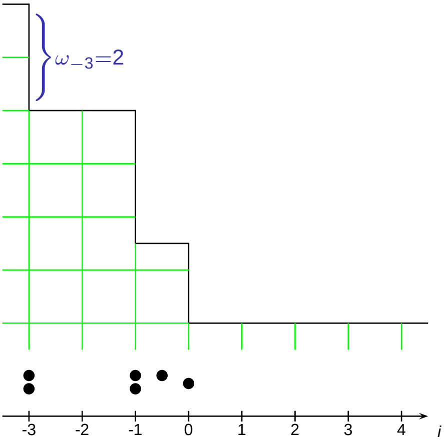

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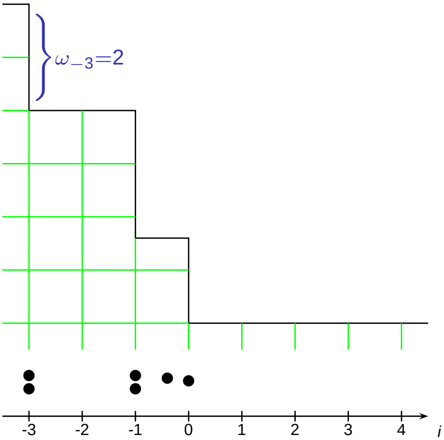

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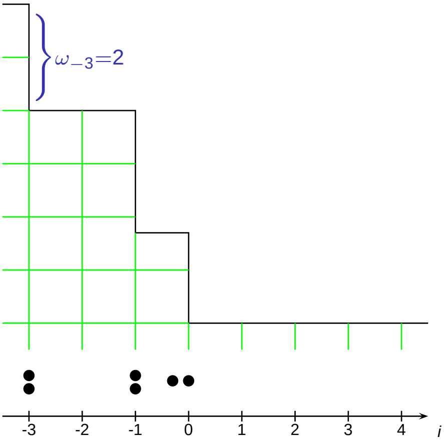

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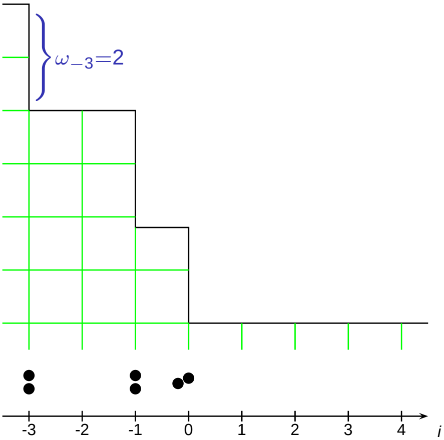

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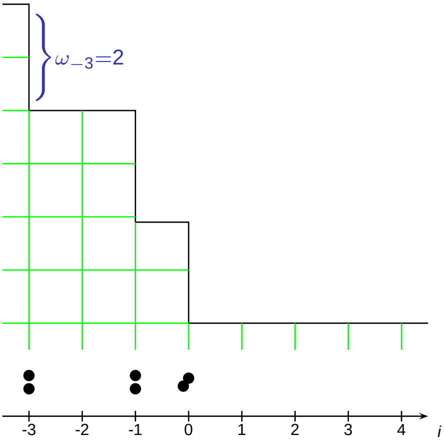

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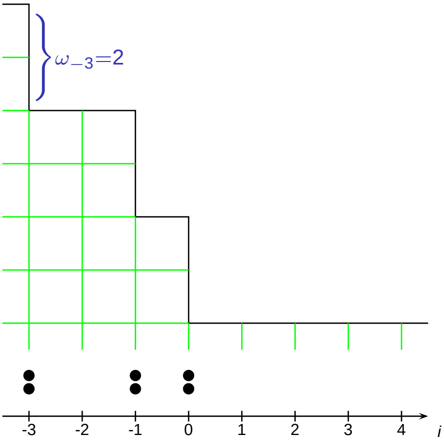

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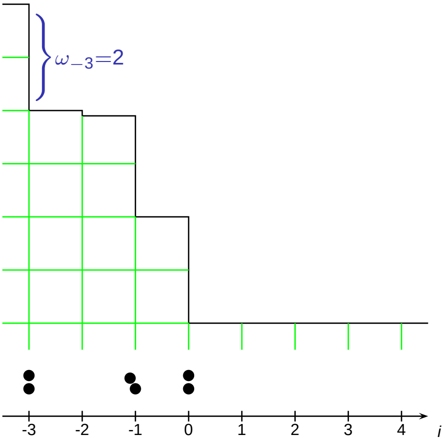

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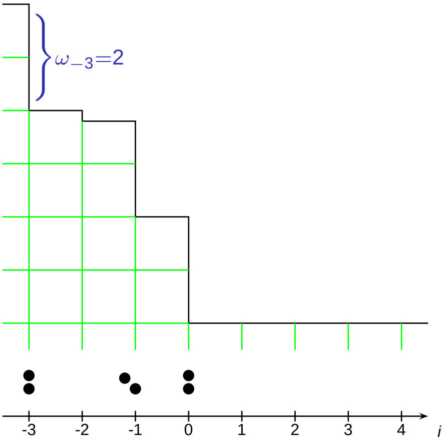

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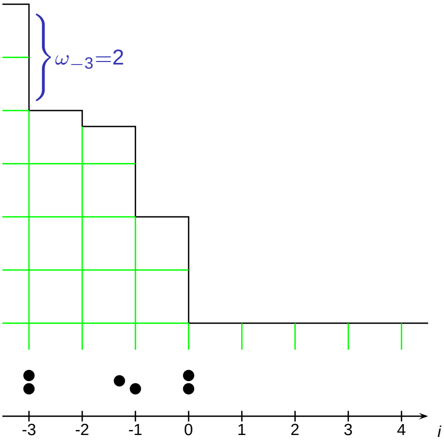

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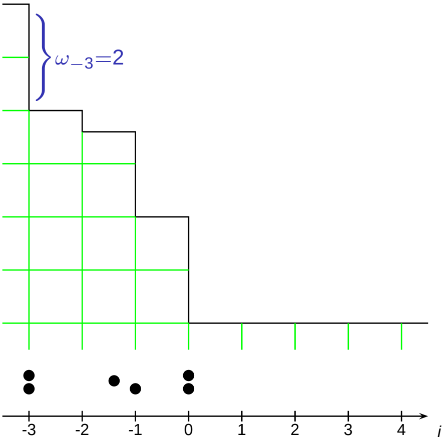

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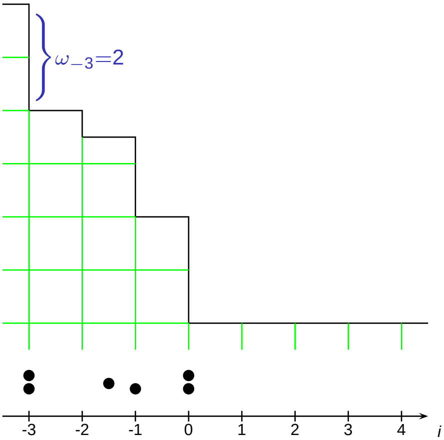

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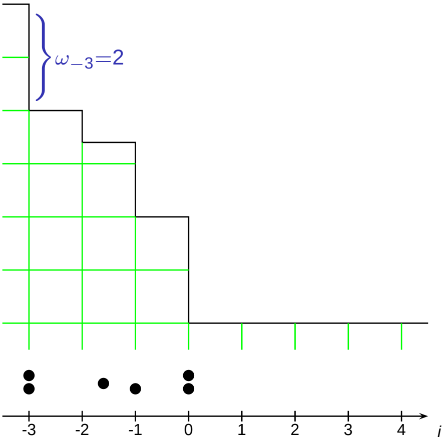

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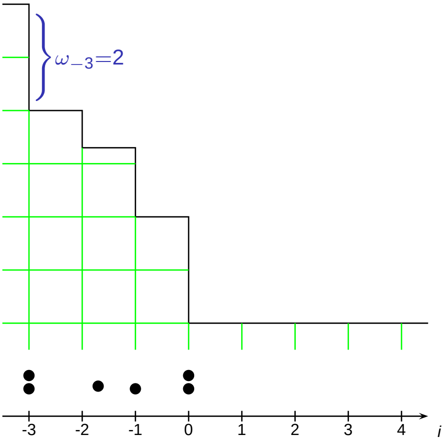

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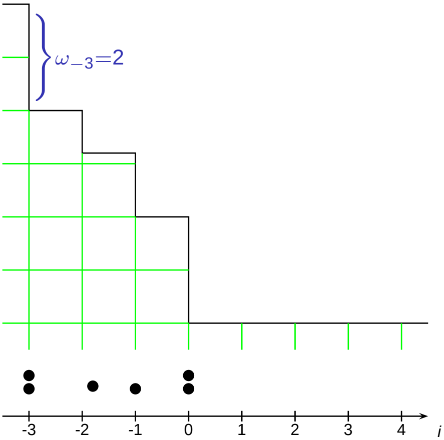

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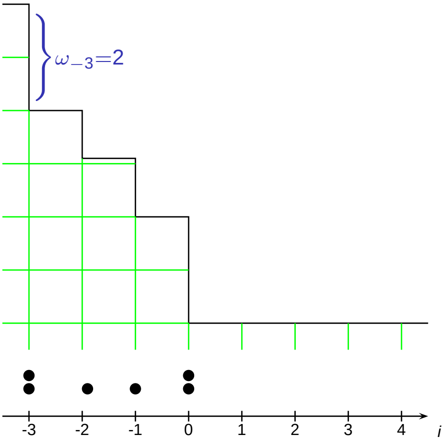

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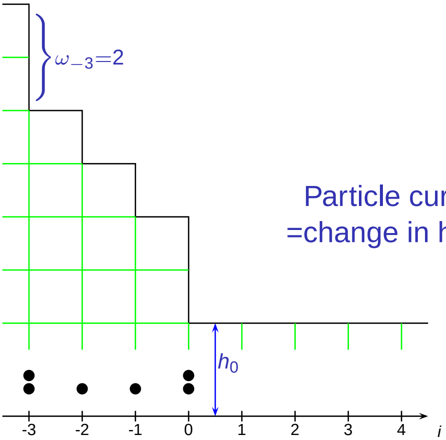

Particle current
=change in height

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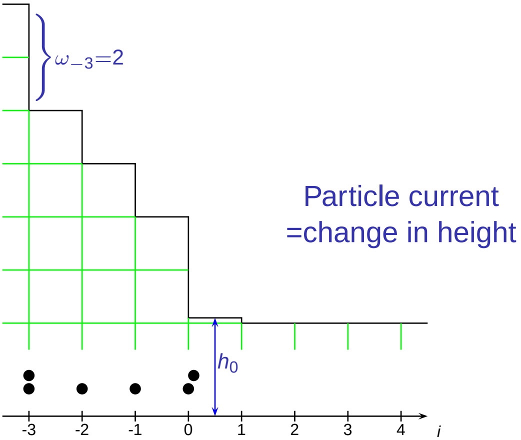

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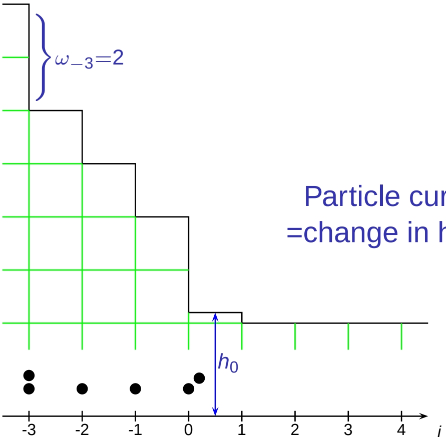

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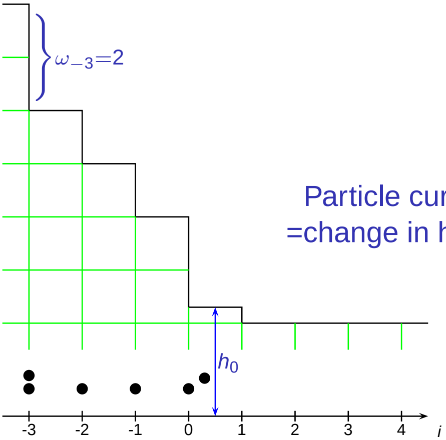

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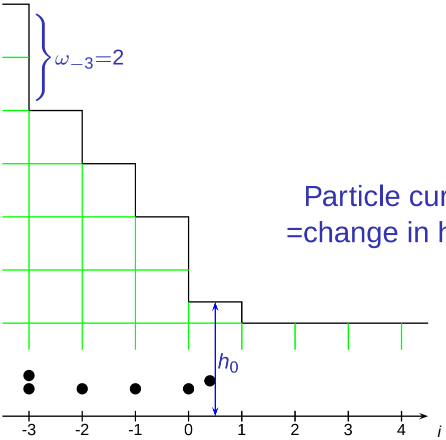

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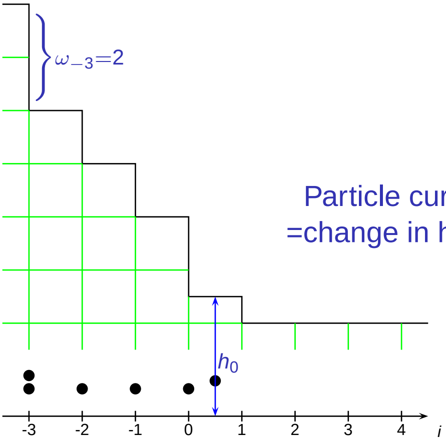

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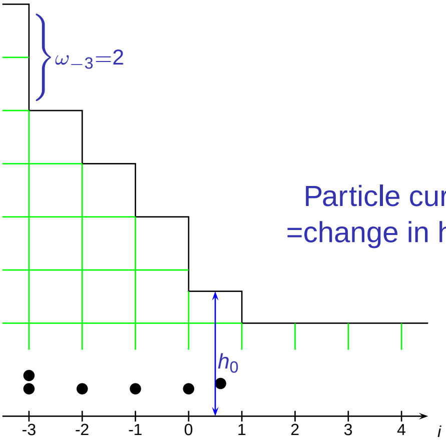

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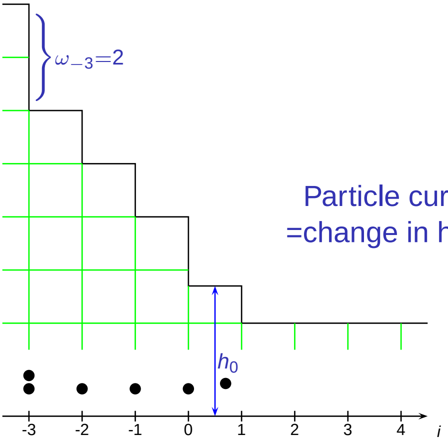

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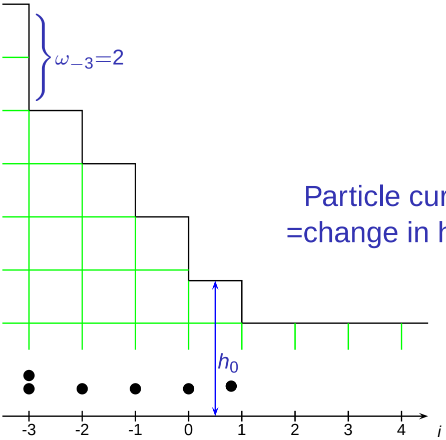

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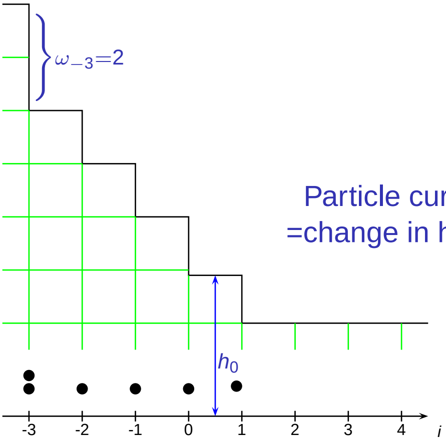

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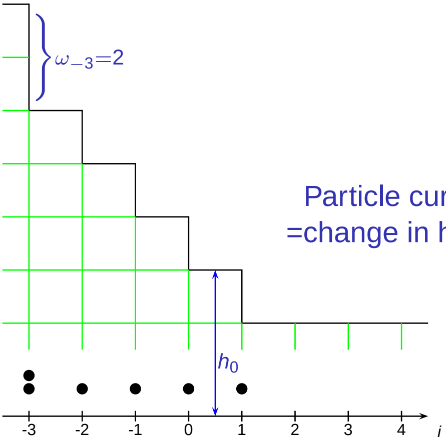

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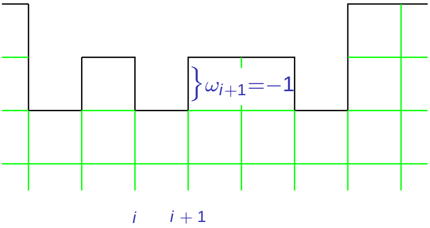
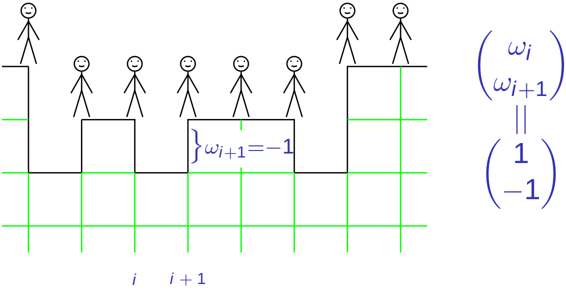
The asymmetric bricklayers process



$$\begin{pmatrix}\omega_i\\ \omega_{i+1}\end{pmatrix} = \begin{pmatrix}1\\ -1\end{pmatrix}$$

Poisson-type distribution; $\omega_i \in \mathbb{Z}$.

The asymmetric bricklayers process



Poisson-type distribution; $\omega_i \in \mathbb{Z}$.

a brick is added with rate $p \cdot [r(\omega_i) + r(-\omega_{i+1})]$
a brick is removed with rate $q \cdot [r(-\omega_i) + r(\omega_{i+1})]$.

$(r(\omega) \cdot r(1-\omega) = 1;\quad r$ non-decreasing; $\quad q = 1 - p < p)$.

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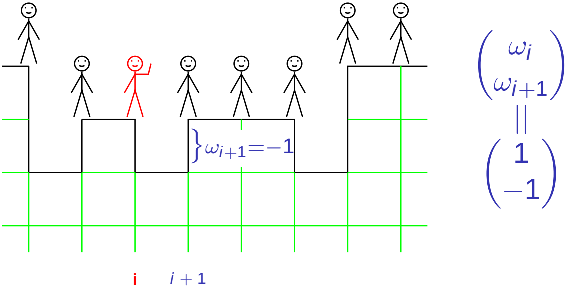

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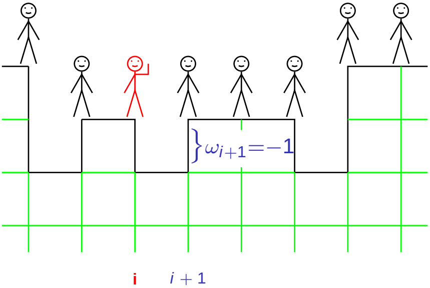
a brick is removed with rate $q \cdot [\mathbf{r}(-\omega_\mathbf{i}) + r(\omega_{i+1})]$.

$(r(\omega) \cdot r(1-\omega) = 1; \quad r$ non-decreasing; $\quad q = 1 - p < p)$.

The asymmetric bricklayers process



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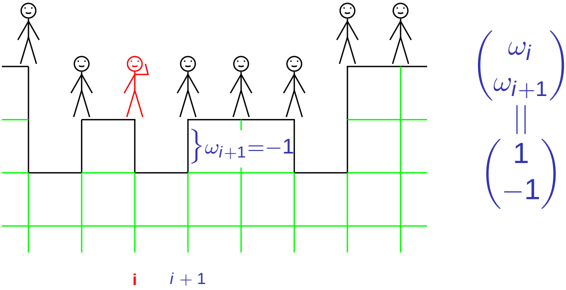

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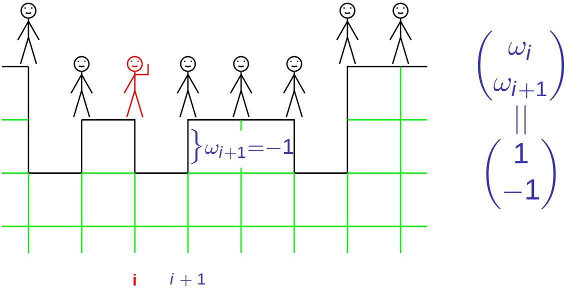

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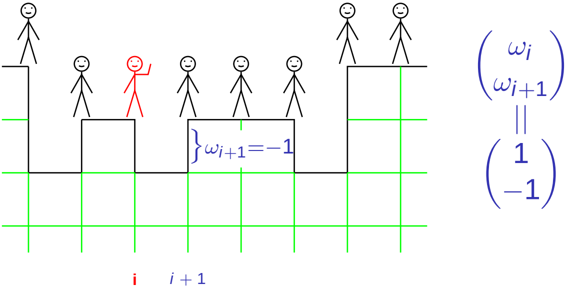

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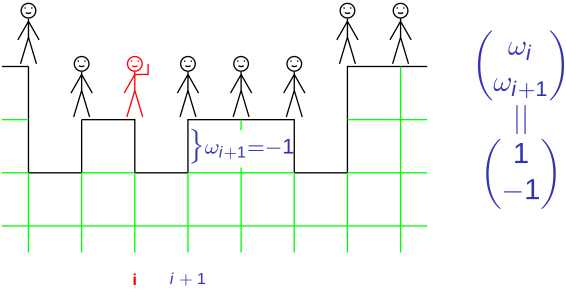

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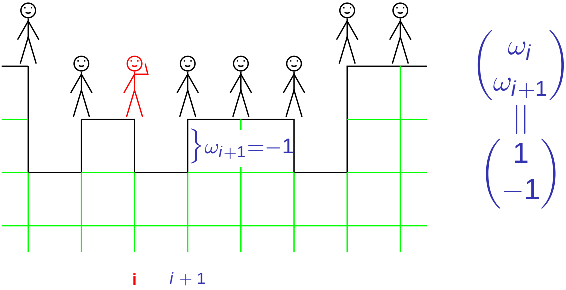

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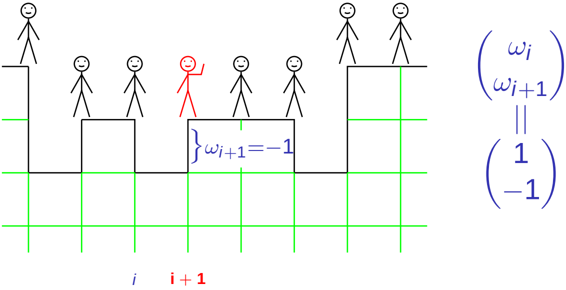

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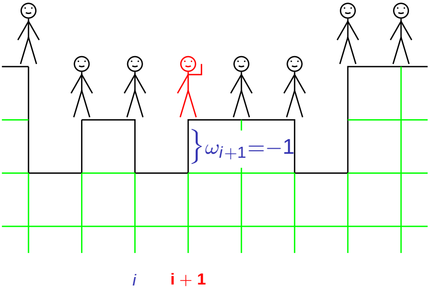

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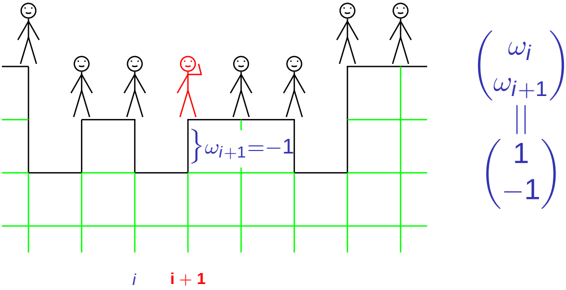

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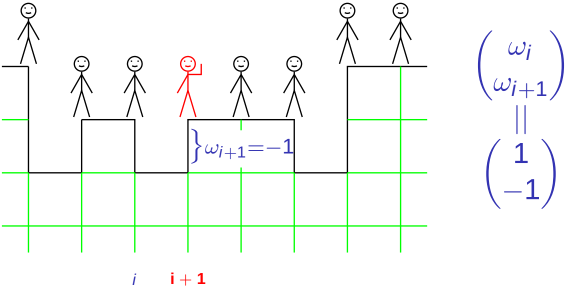

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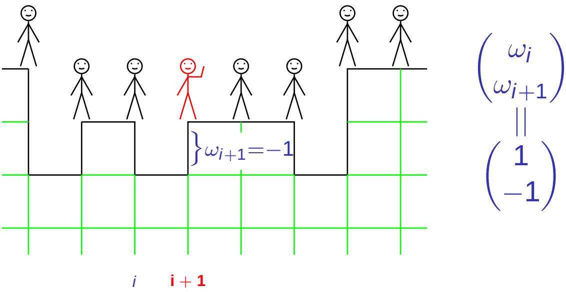

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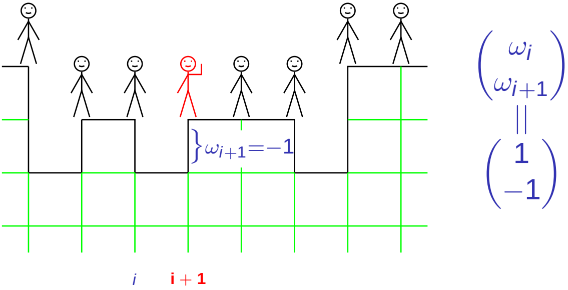

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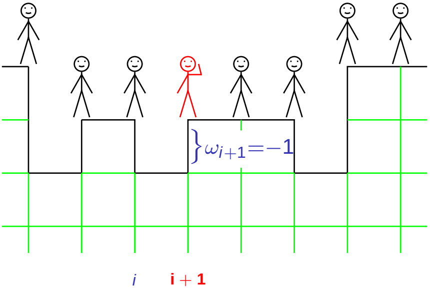

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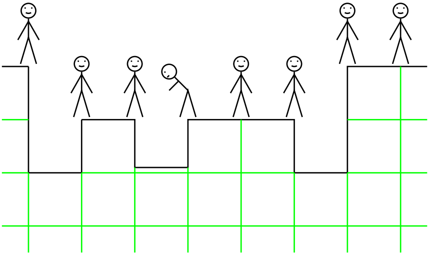

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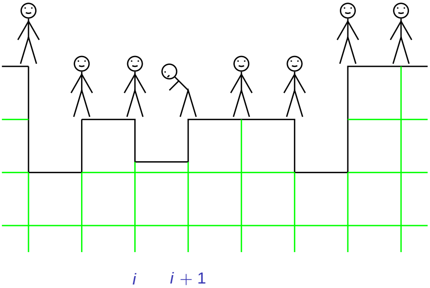

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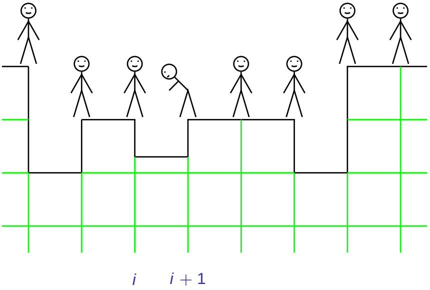

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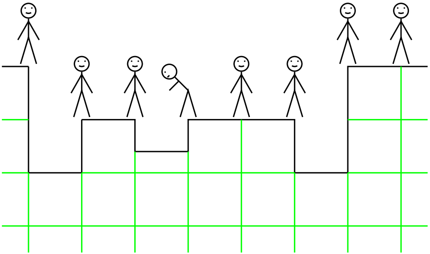

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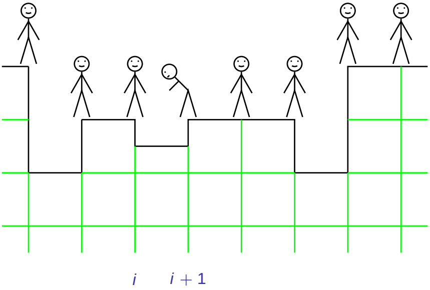

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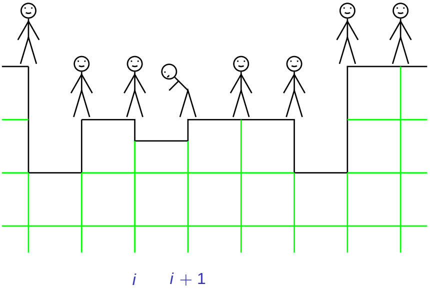

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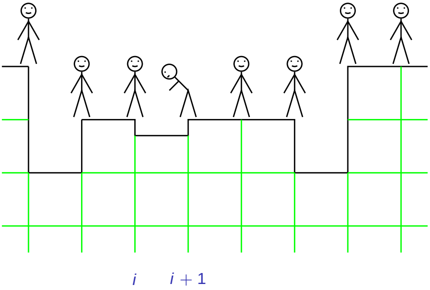

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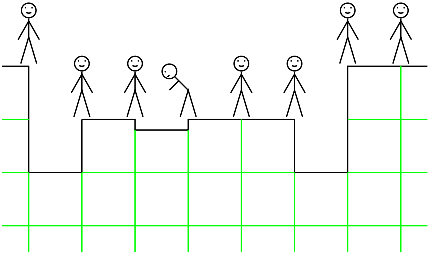

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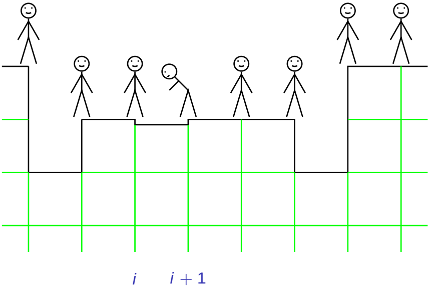

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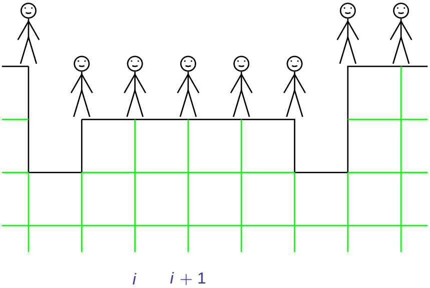

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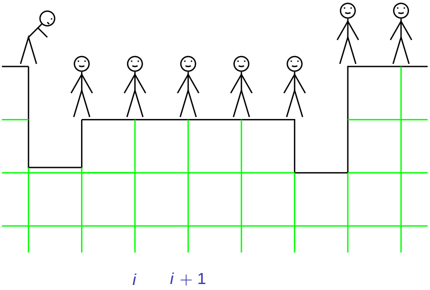

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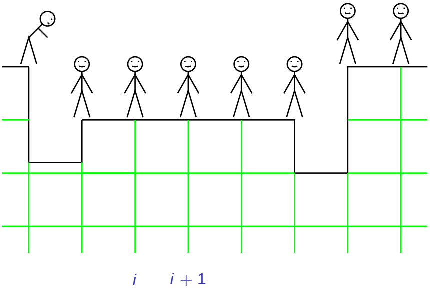

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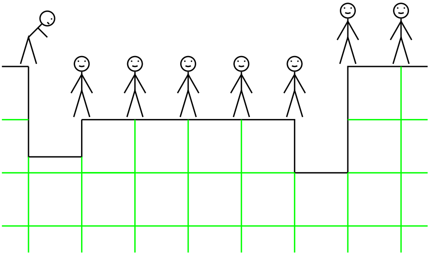

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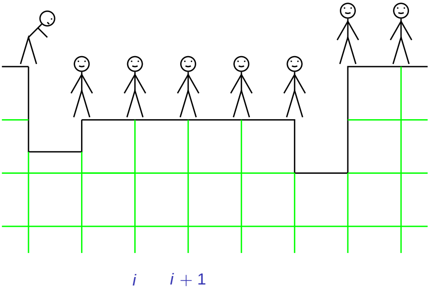

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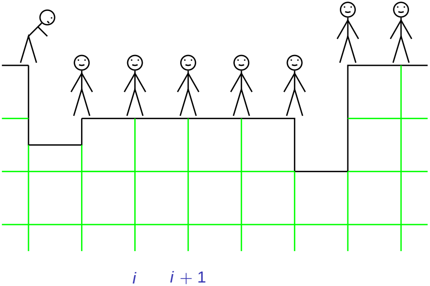

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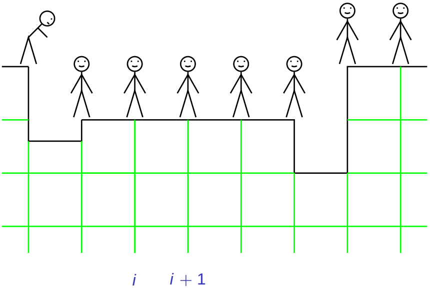

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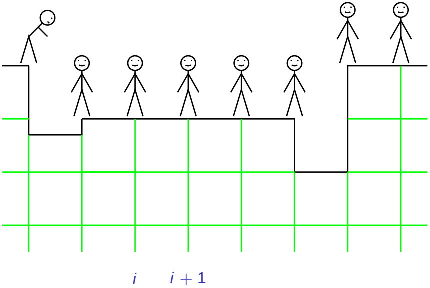

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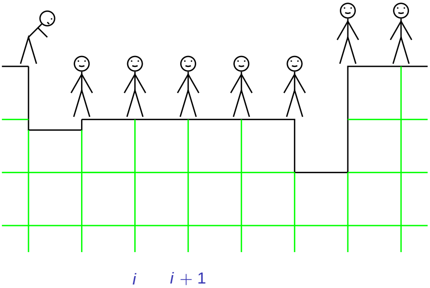

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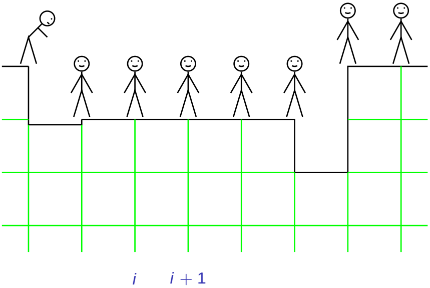

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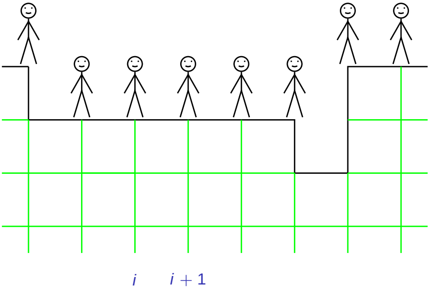

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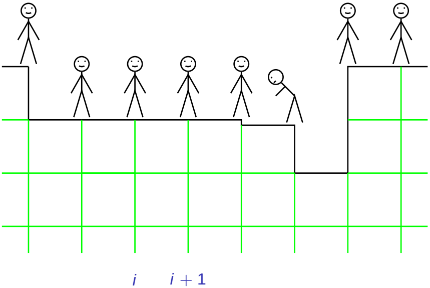

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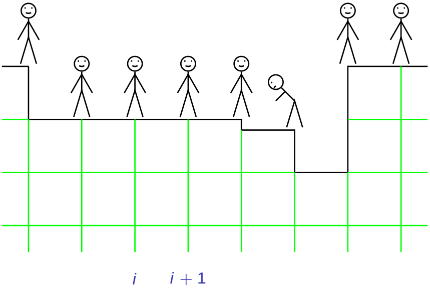

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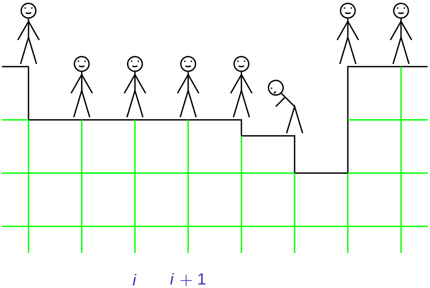

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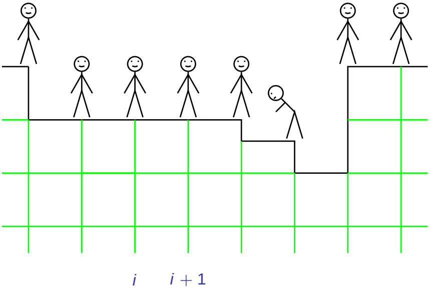

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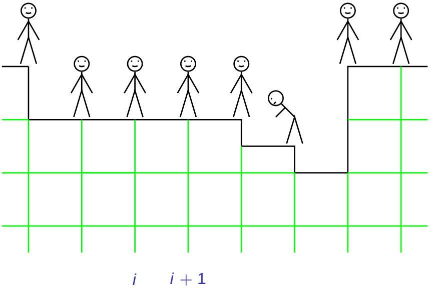

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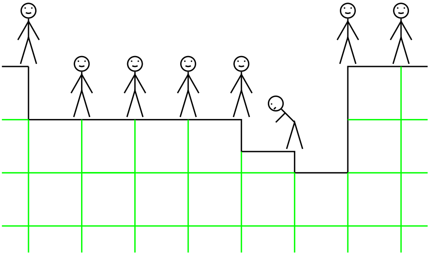

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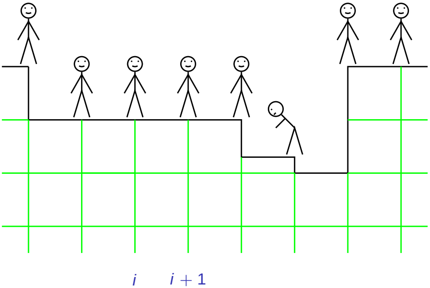

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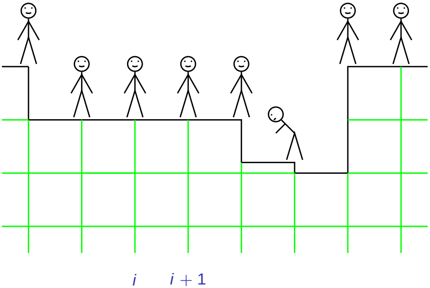

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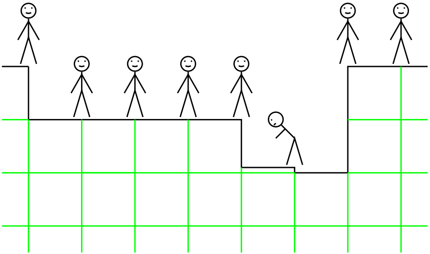

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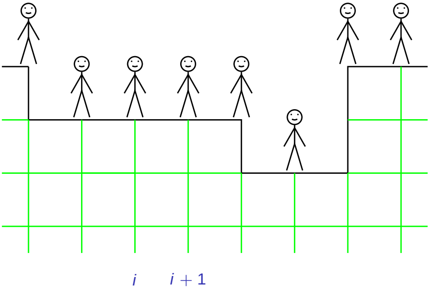

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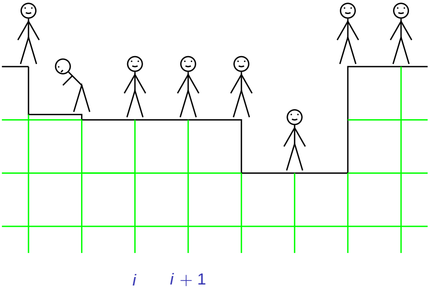

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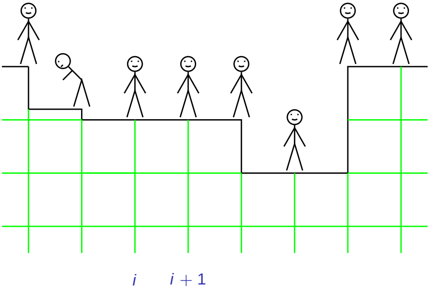

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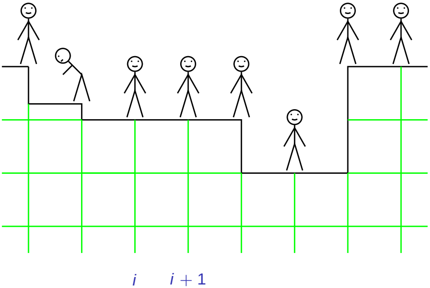

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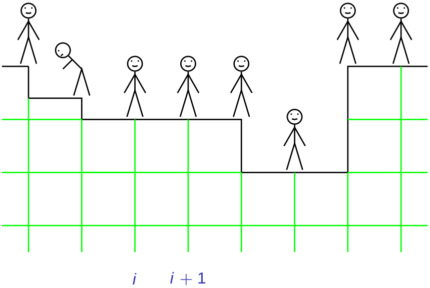

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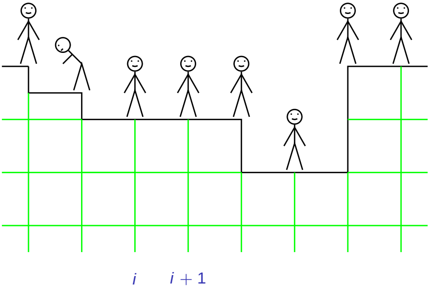

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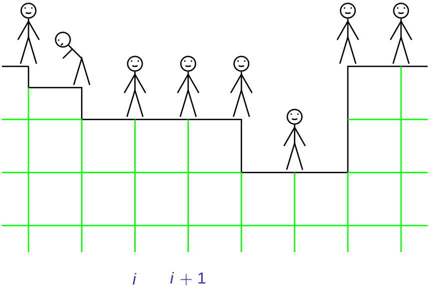

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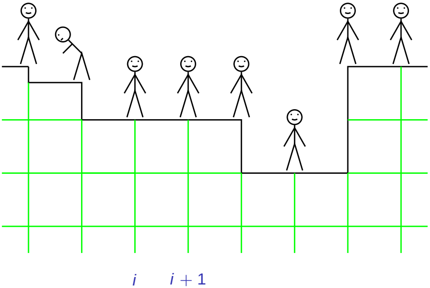

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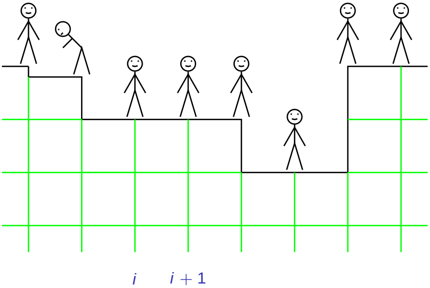

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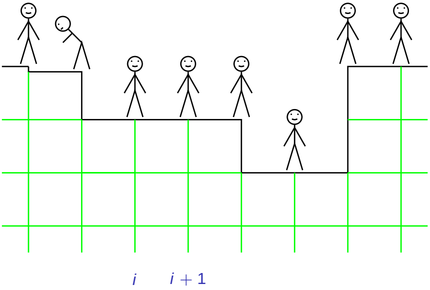

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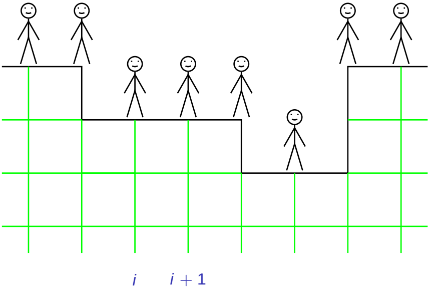

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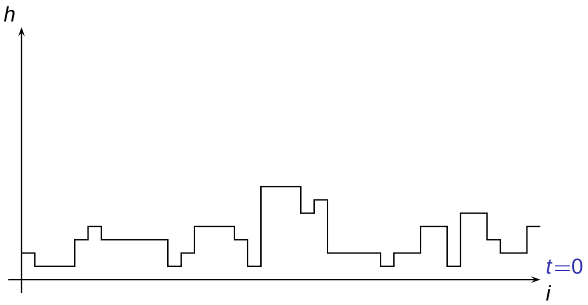

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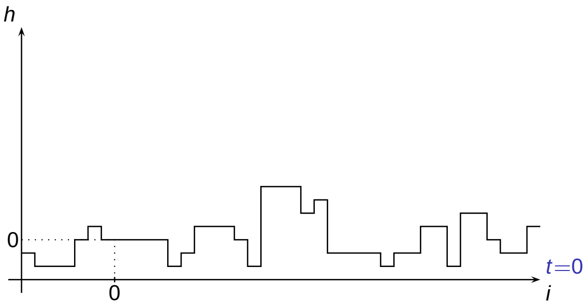

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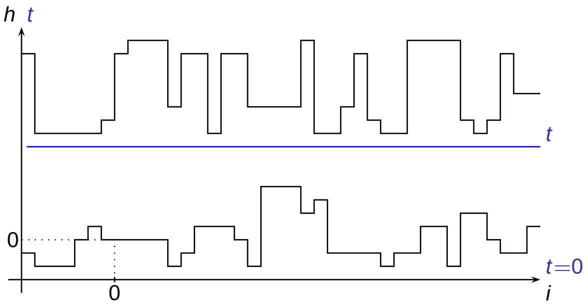

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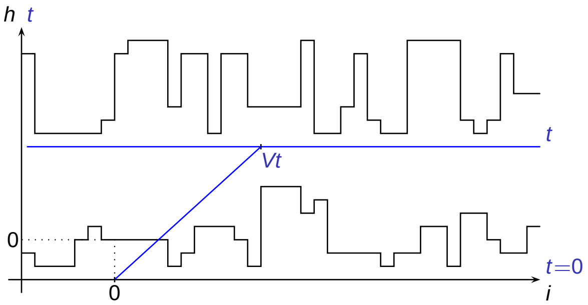

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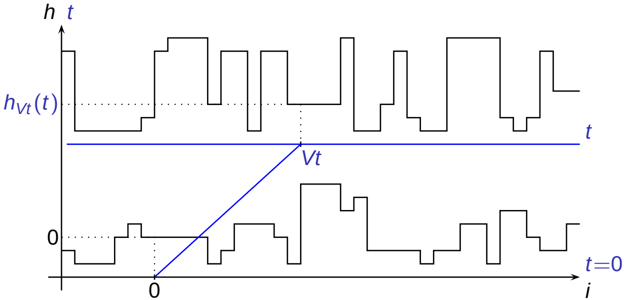

$h_{Vt}(t)$ = height as seen by a moving observer of velocity V.

= net number of particles passing the window $s \mapsto Vs$.

(Remember: particle current=change in height.)

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If $H(\varrho)$ is convex or concave, then *the Rankine-Hugoniot speed for densities* ϱ *and* λ is

$$R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}.$$

Characteristics (very briefly)

$$\partial_T \varrho + \partial_X H(\varrho) = 0$$

$$\partial_T \varrho + H'(\varrho) \cdot \partial_X \varrho = 0 \qquad \text{(while smooth)}$$

$$\partial_T \varrho + \dot{X}(T) \cdot \partial_X \varrho = \frac{\mathrm{d}}{\mathrm{d}T} \varrho(T, X(T)) = 0$$

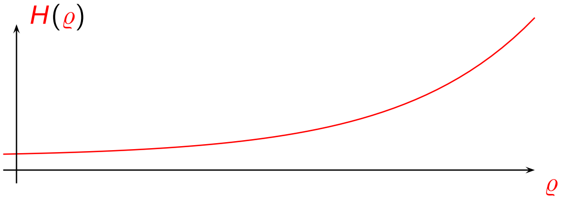
So, $\dot{X}(T) = H'(\varrho) =: C$ is the *characteristic speed*.
If $H(\varrho)$ is convex or concave, then *the Rankine-Hugoniot speed for densities* ϱ *and* λ is

$$R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}.$$

This would be the speed of a shock of densities ϱ and λ.

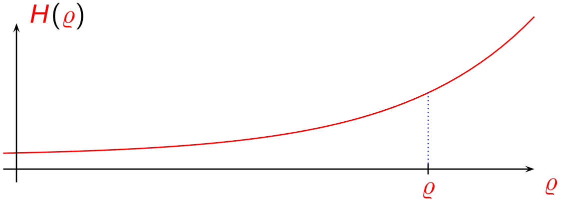
Characteristics (very briefly)

Convex flux (some cases of AZRP, ABLP):



Characteristics (very briefly)

Convex flux (some cases of AZRP, ABLP):



Characteristics (very briefly)

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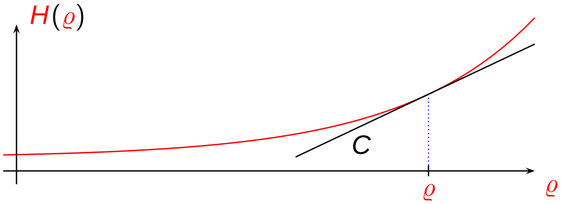
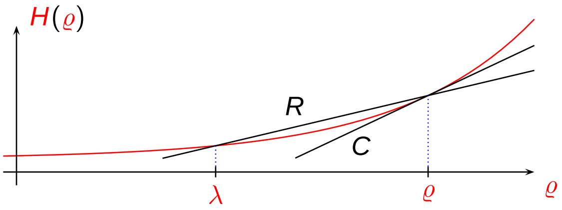


$$C = H'(\varrho)$$

Characteristics (very briefly)

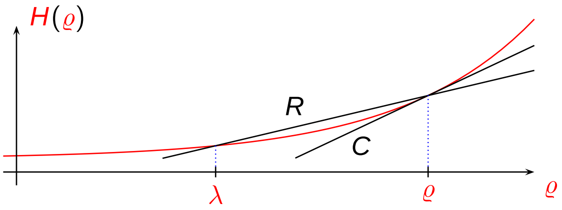
Convex flux (some cases of AZRP, ABLP):



$$C = H'(\varrho) \qquad R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}$$

Characteristics (very briefly)

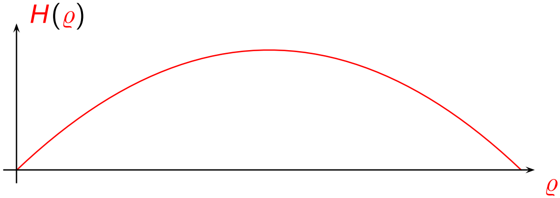
Convex flux (some cases of AZRP, ABLP):



$$C = H'(\varrho) > R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}$$

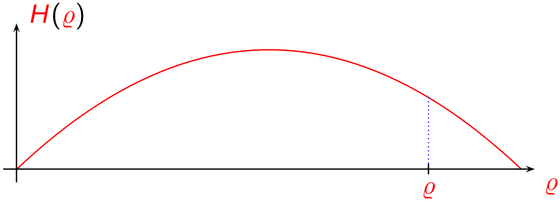
Characteristics (very briefly)

Concave flux (ASEP, AZRP):



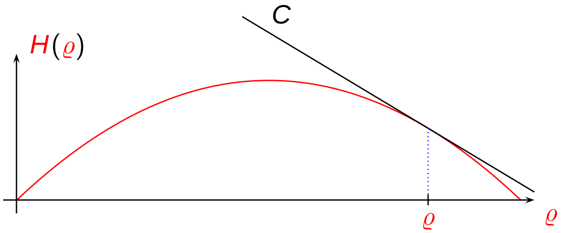
Characteristics (very briefly)

Concave flux (ASEP, AZRP):



Characteristics (very briefly)

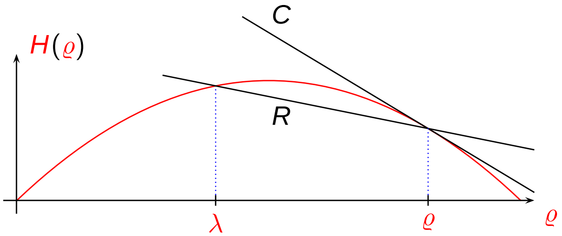
Concave flux (ASEP, AZRP):



$$C = H'(\varrho)$$

Characteristics (very briefly)

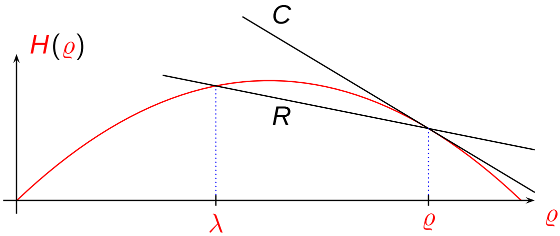
Concave flux (ASEP, AZRP):



$$C = H'(\varrho) \qquad R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}$$

Characteristics (very briefly)

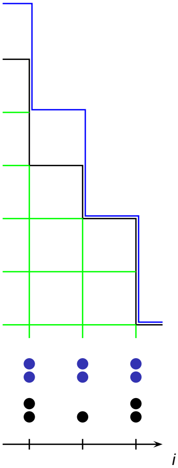
Concave flux (ASEP, AZRP):



$$C = H'(\varrho) < R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}$$

Tool: the second class particle

States ω and ω only differ at one site.



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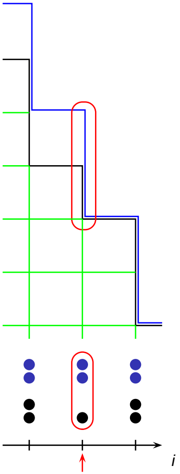

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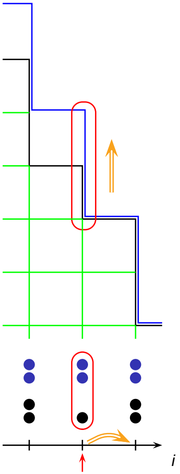
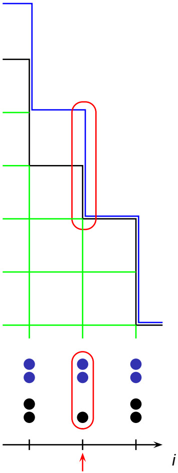


Growth on the right:

rate≤rate

Tool: the second class particle

States ω and ω only differ at one site.



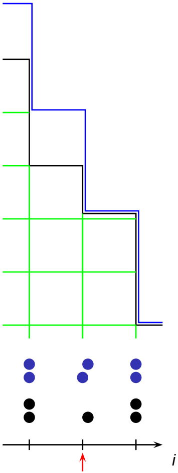
Growth on the right:

rate$\leq$rate

with rate:

Tool: the second class particle

States ω and ω only differ at one site.



Growth on the right:

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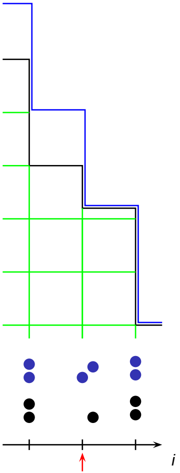

Growth on the right:

rate≤rate

with rate:

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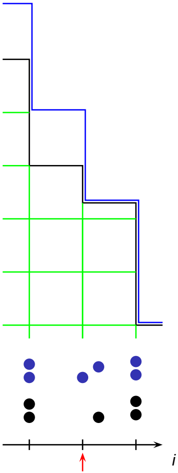

Growth on the right:

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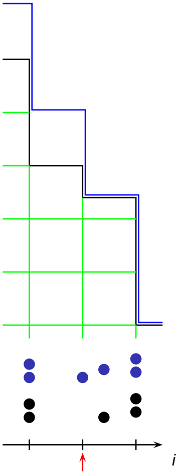

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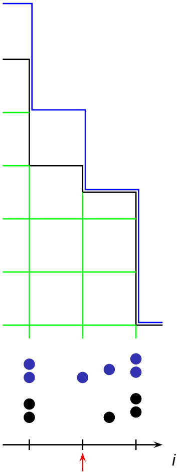

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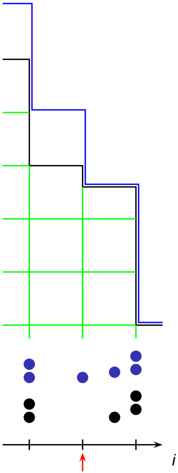

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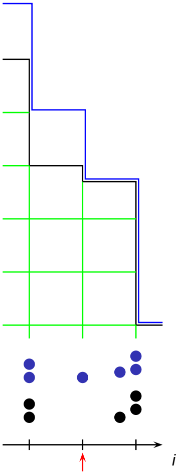

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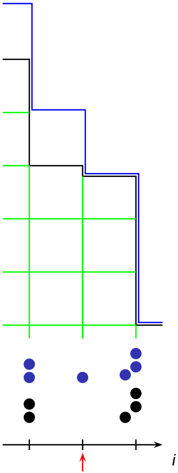

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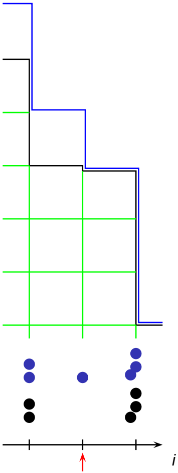

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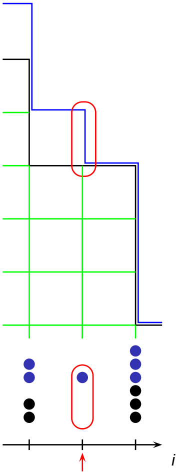


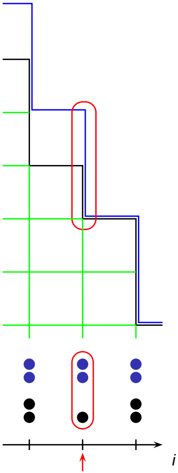
Growth on the right:

rate≤rate

with rate:

Tool: the second class particle

States ω and ω only differ at one site.



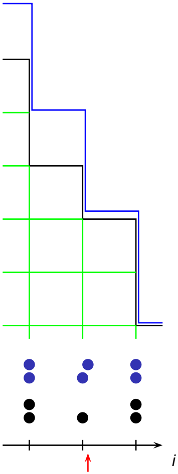
Growth on the right:

rate≤rate

with rate-rate:

Tool: the second class particle

States ω and ω only differ at one site.



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with rate-rate:

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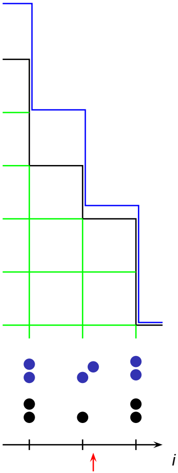

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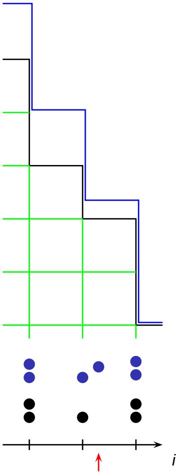

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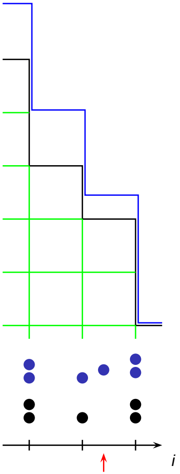

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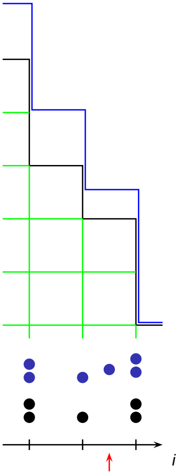

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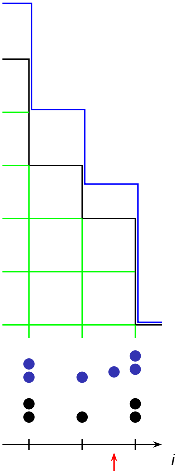

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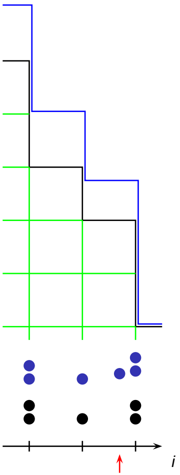

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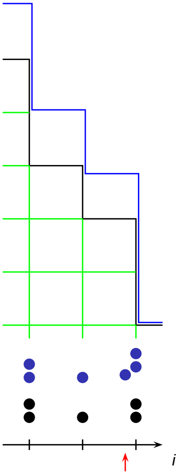

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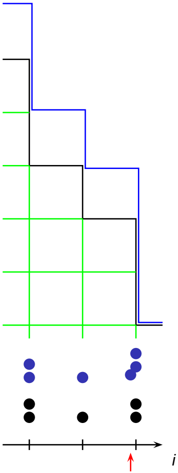

Growth on the right:

rate≤rate

with rate-rate:

Tool: the second class particle

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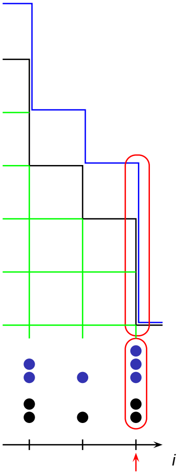


Growth on the right:

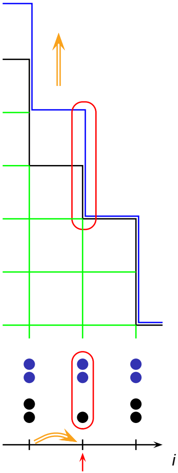
rate$\leq$rate

with rate-rate:

Tool: the second class particle

States ω and ω only differ at one site.

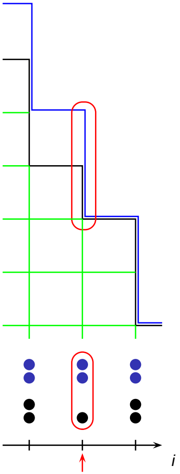
Growth on the left:
rate$\geq$rate



Tool: the second class particle

States ω and ω only differ at one site.

Growth on the left:
rate$\geq$rate
with rate:



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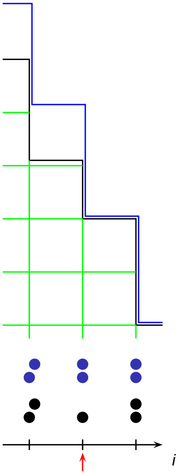

Tool: the second class particle

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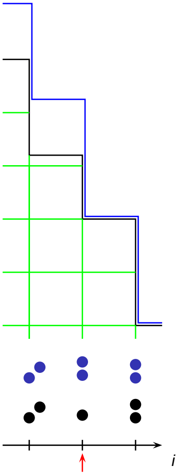

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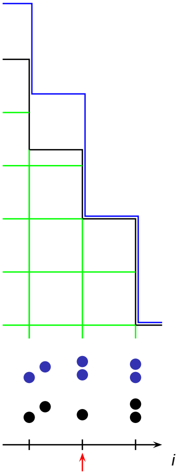

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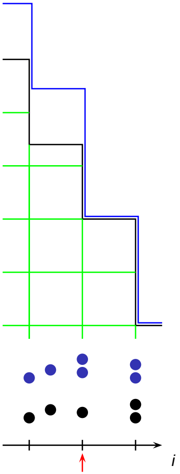

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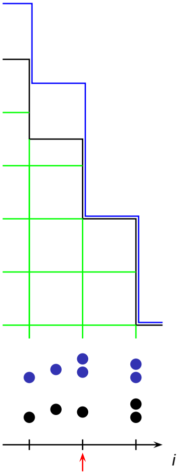

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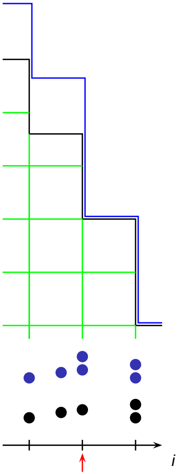

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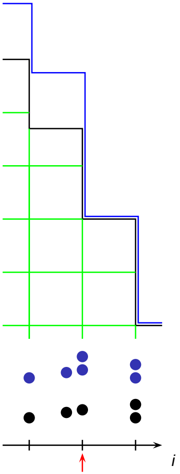

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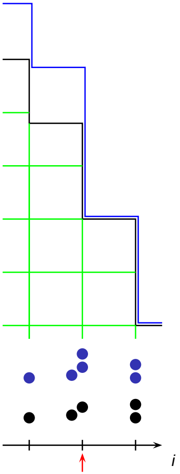

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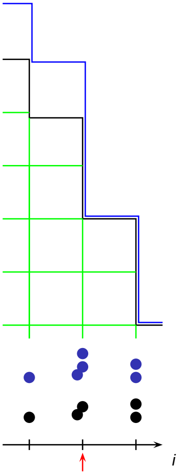

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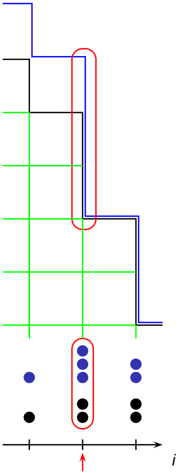
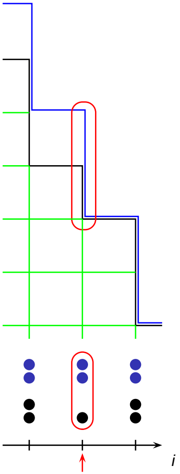
with rate:



Tool: the second class particle

States ω and ω only differ at one site.

Growth on the left:
rate$\geq$rate
with rate-rate:



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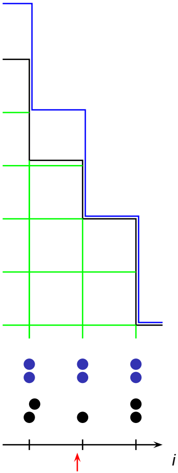

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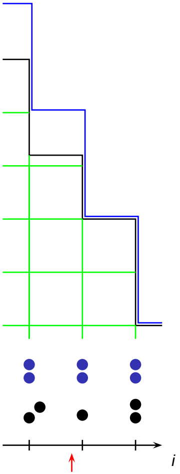

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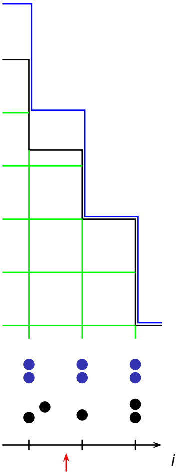

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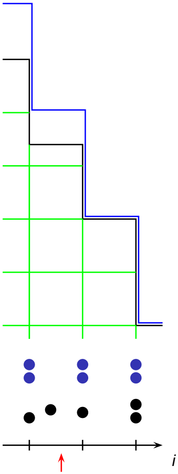

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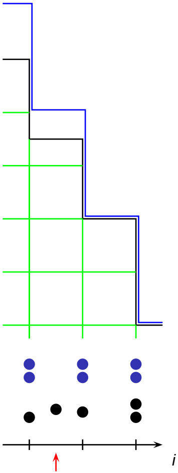

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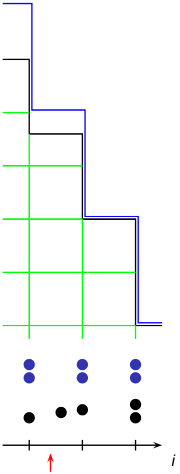

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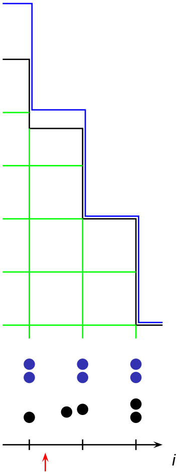

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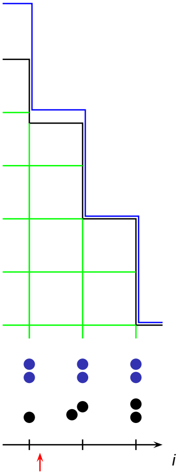
with rate-rate:



Tool: the second class particle

States ω and ω only differ at one site.

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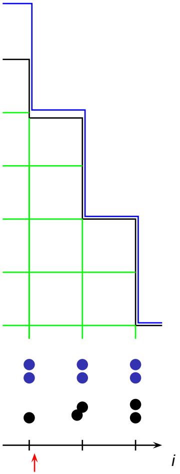
with rate-rate:



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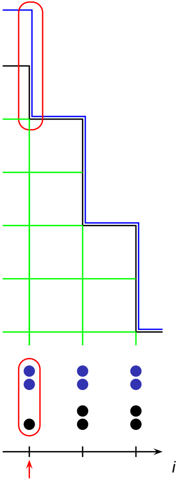

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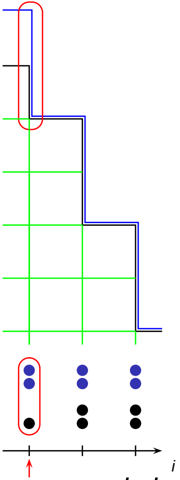

A single discrepancy↑, the *second class particle*, is conserved.
Its position at time t is $Q(t)$.

Tool: the second class particle

Theorem (B. - Seppäläinen; also ideas from B. Tóth, H. Spohn and M. Prähofer**)**

Started from (almost) equilibrium,

$$\mathbf{E}(Q(t)) = C \cdot t$$

in the whole family of processes.

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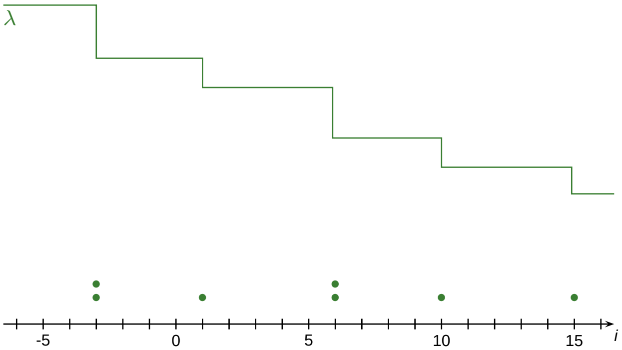
C is the characteristic speed.

The second class particle follows the characteristics, people have known this for a long time.

Many second class particles



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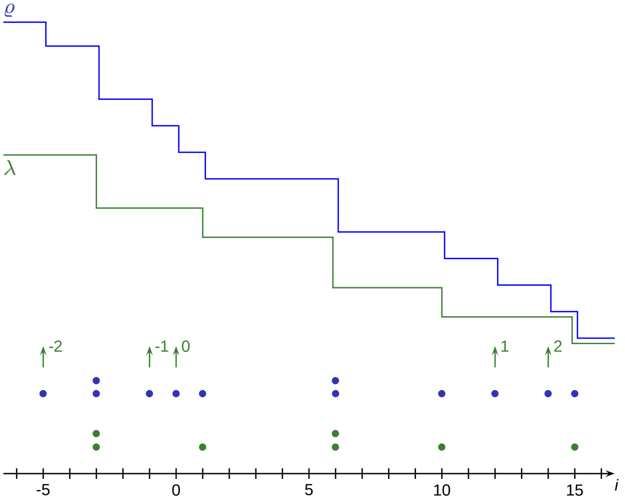

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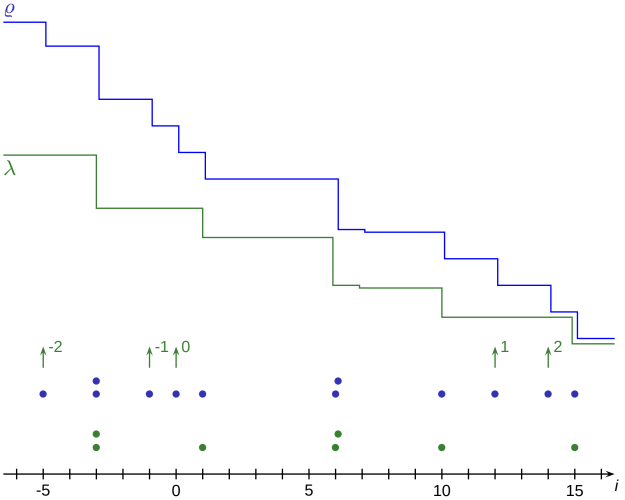

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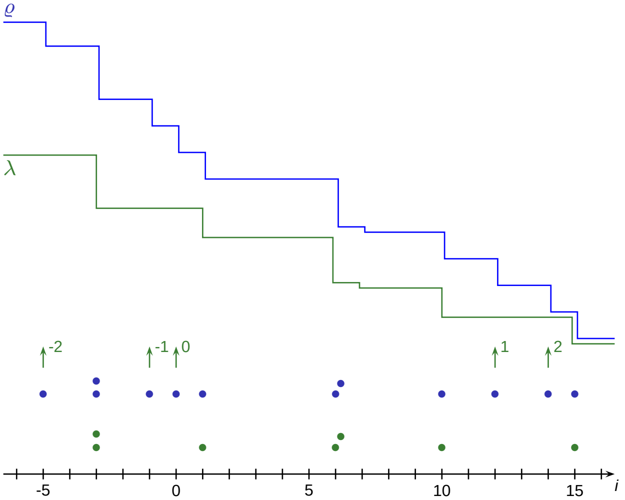

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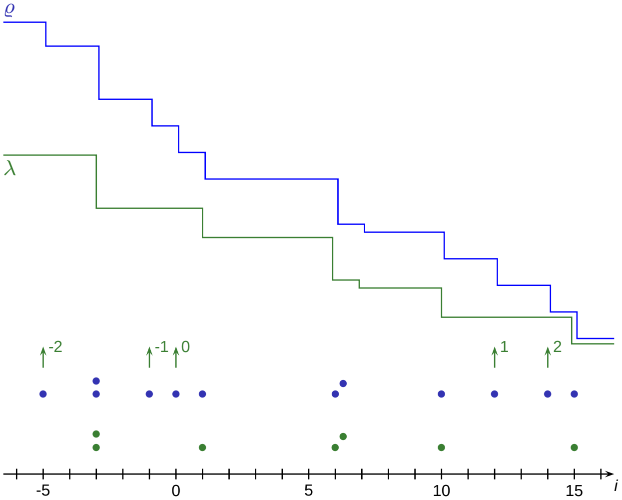

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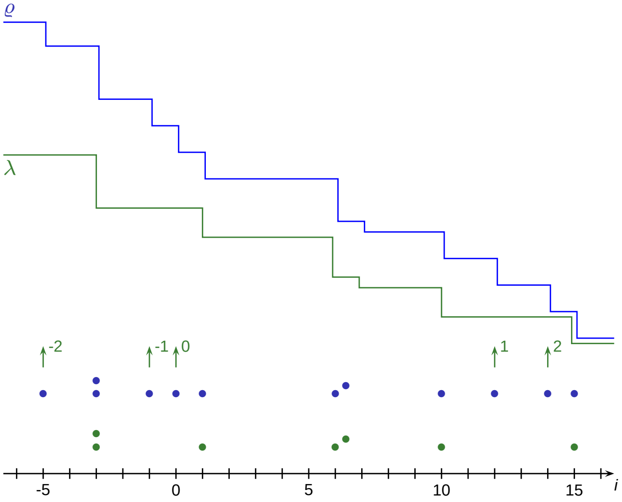

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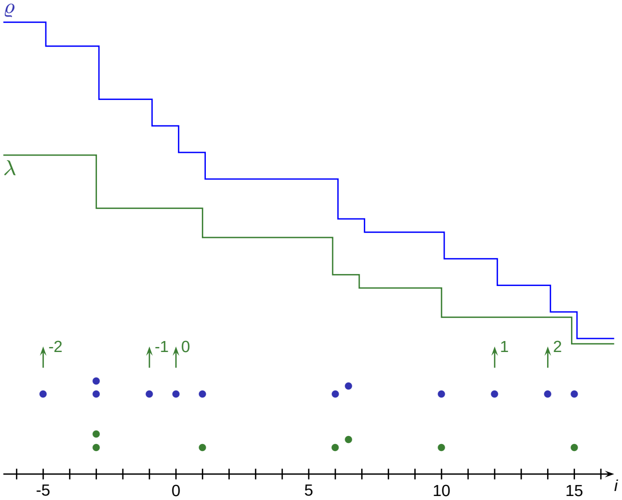

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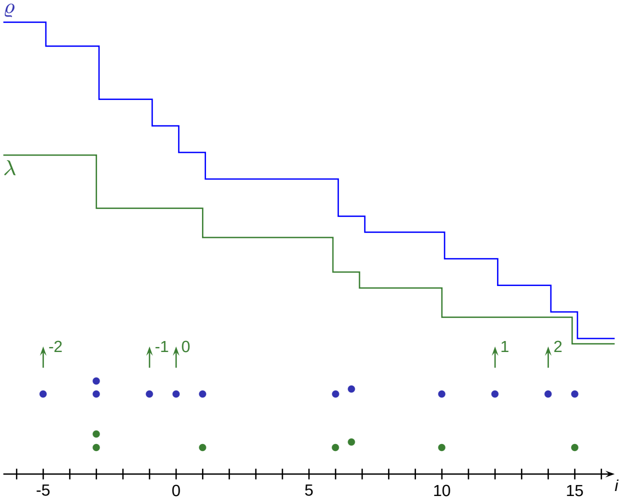

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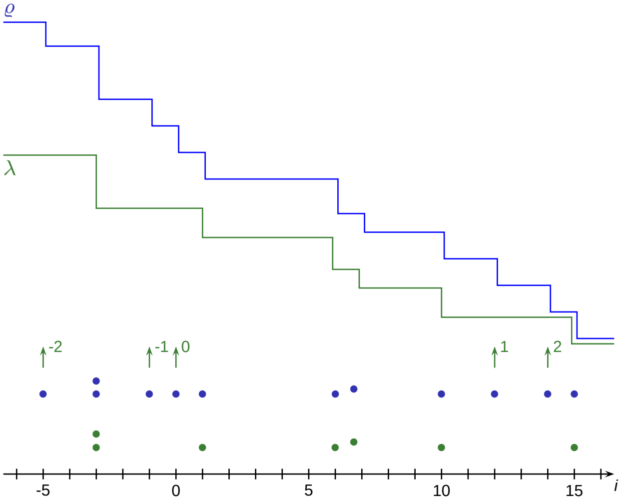

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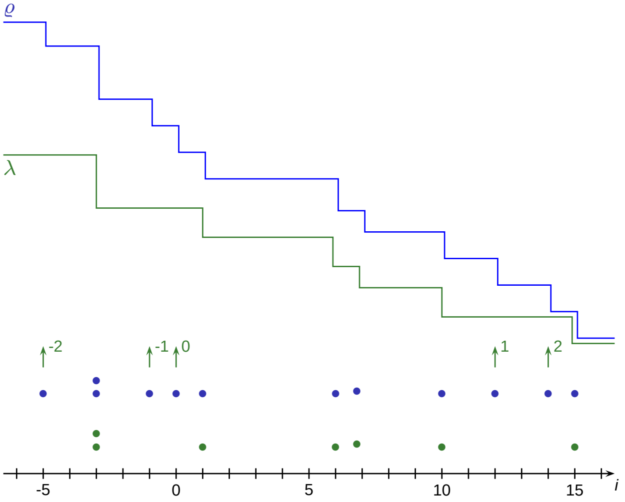

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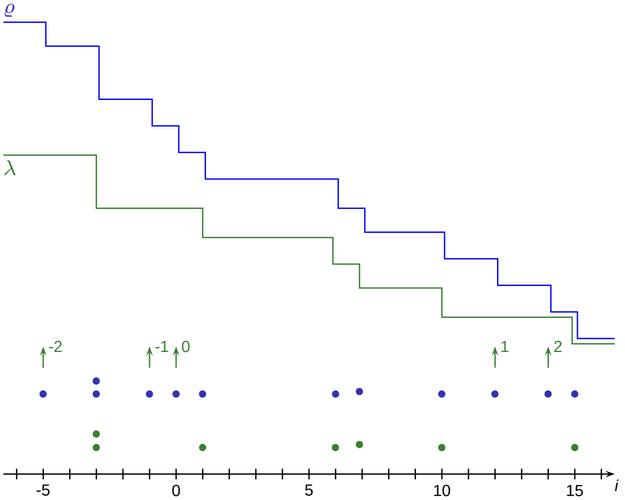

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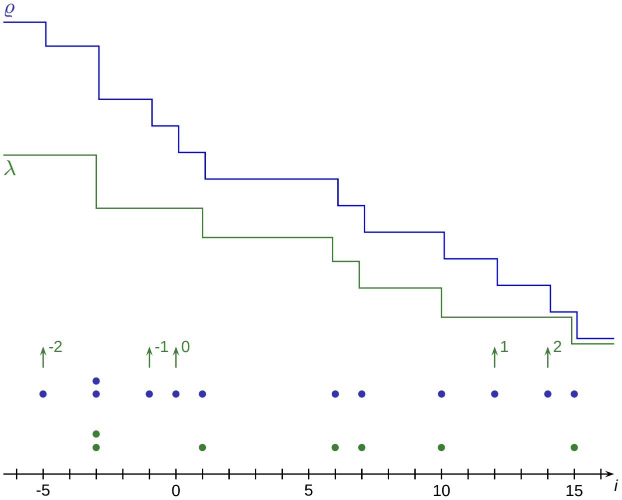

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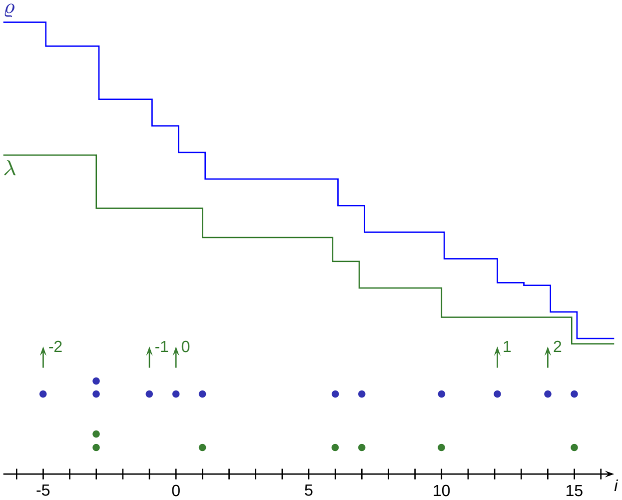

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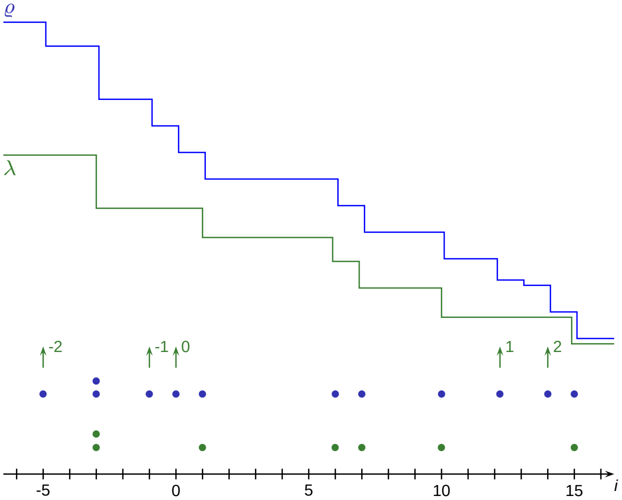

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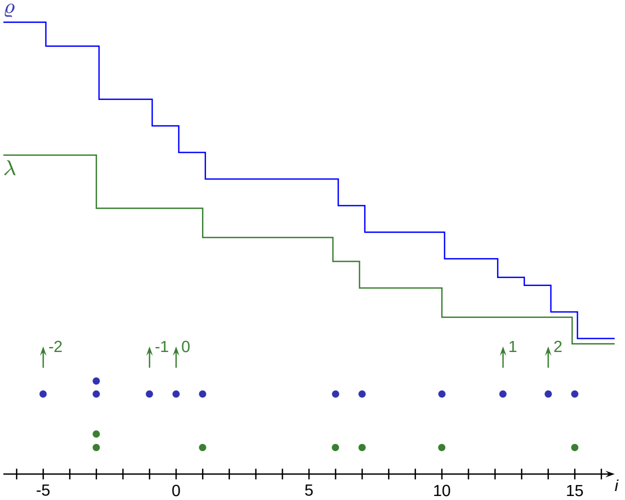

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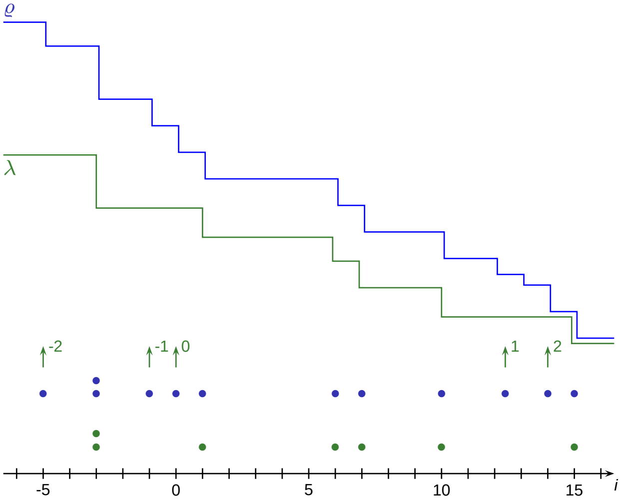

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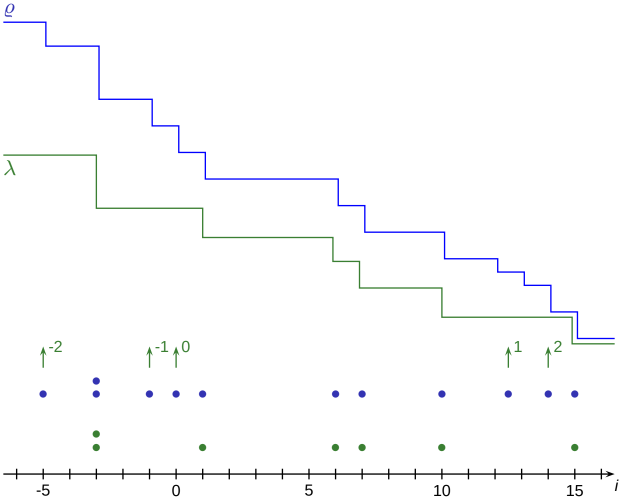

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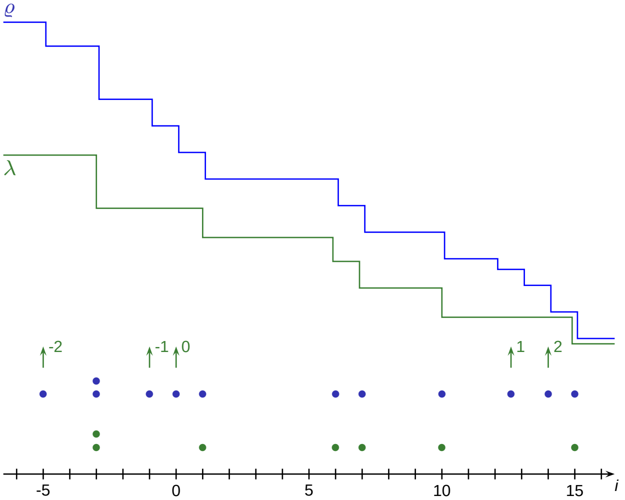

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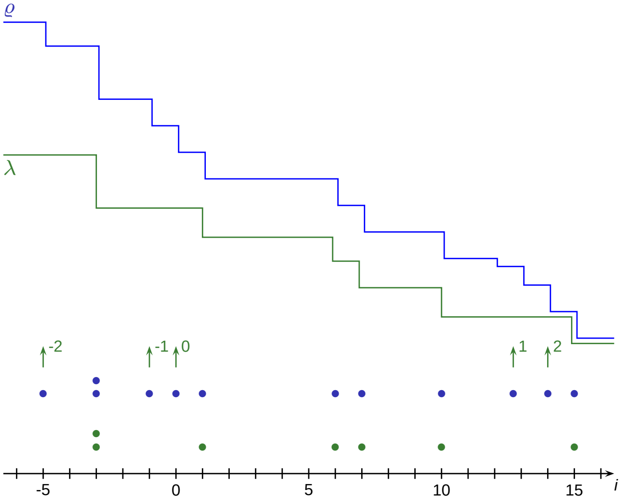

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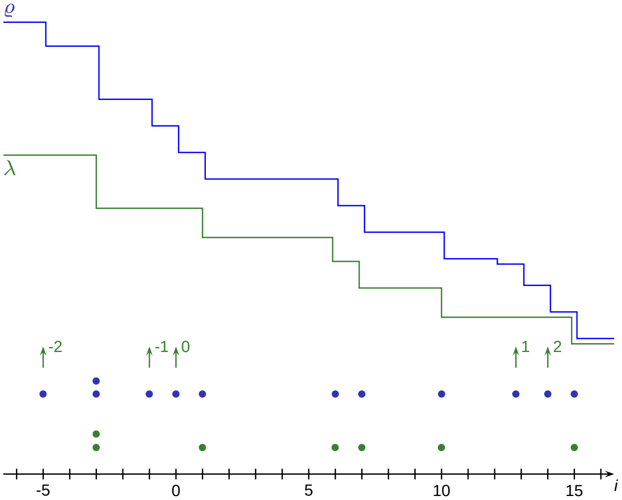

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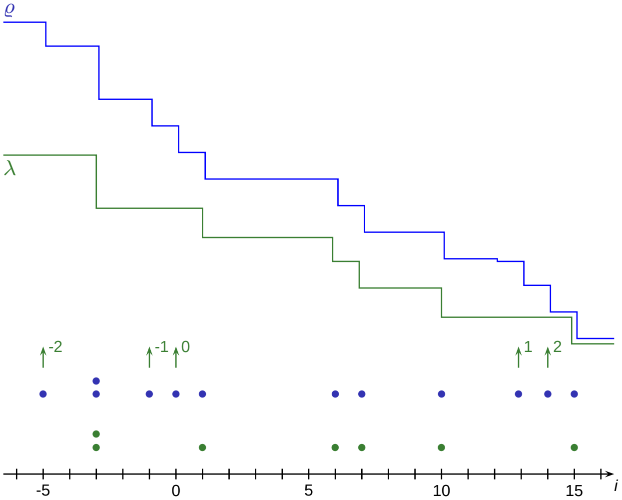

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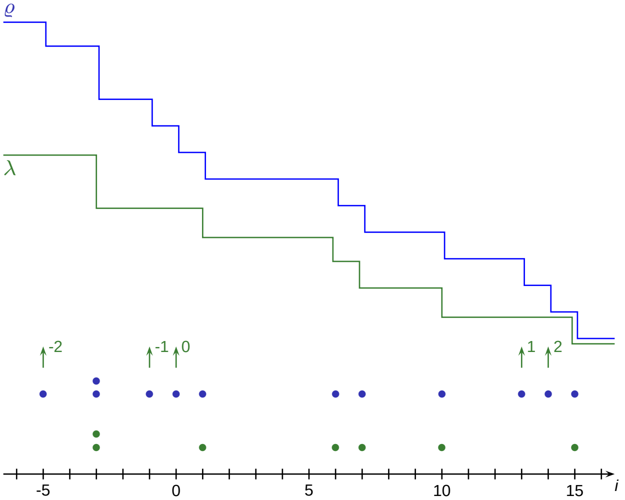

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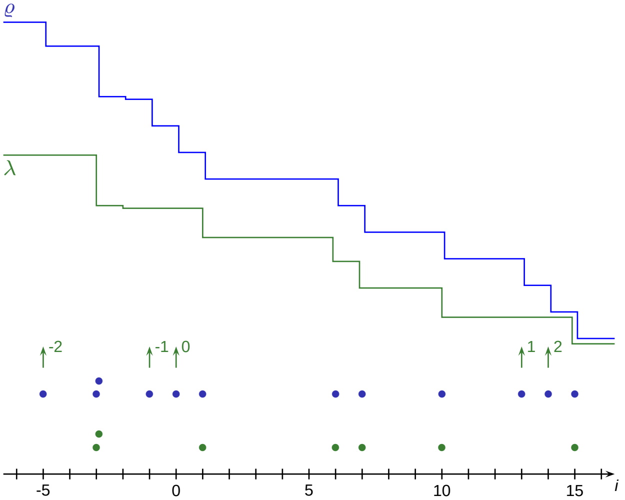

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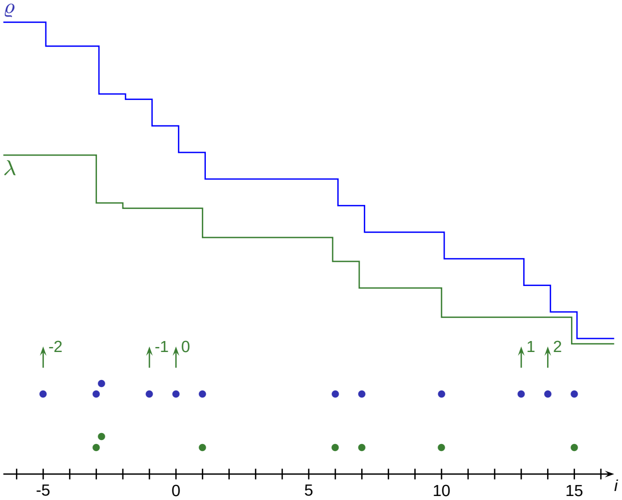

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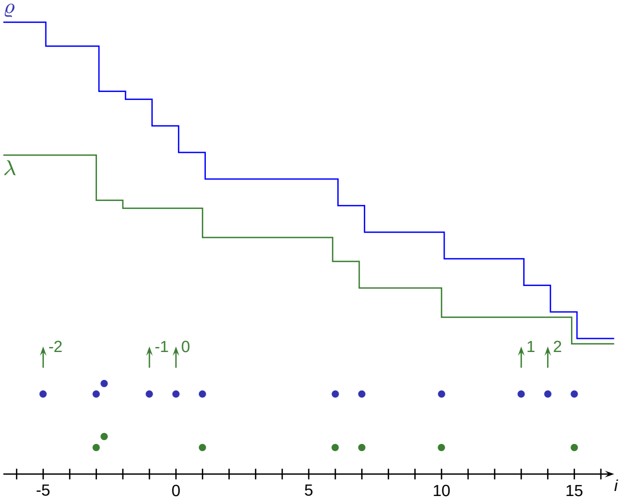

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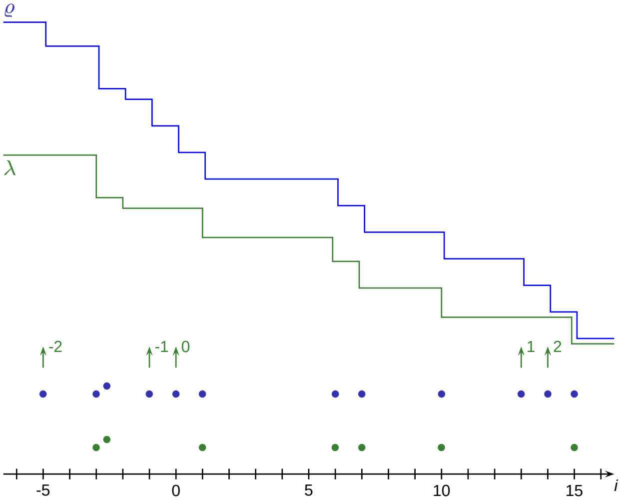

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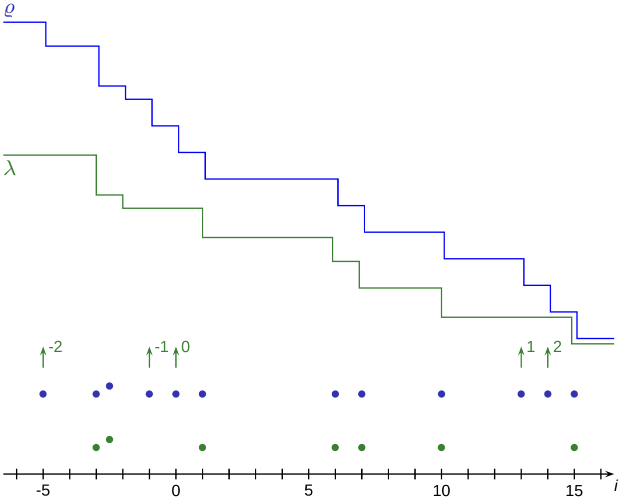

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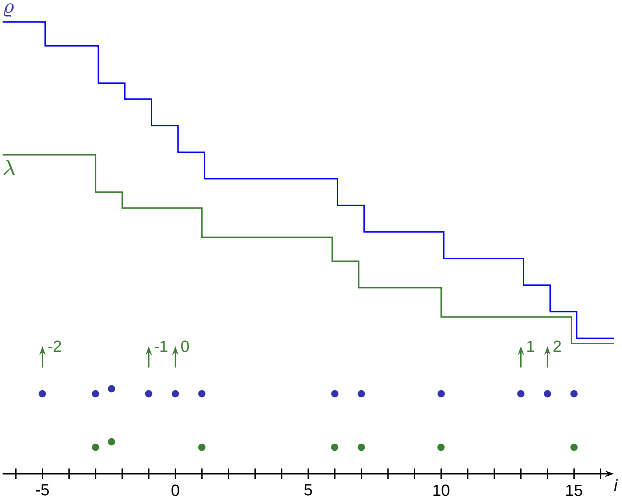

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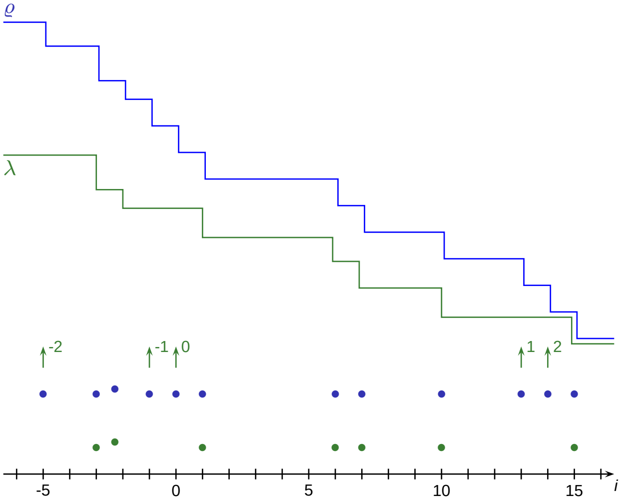

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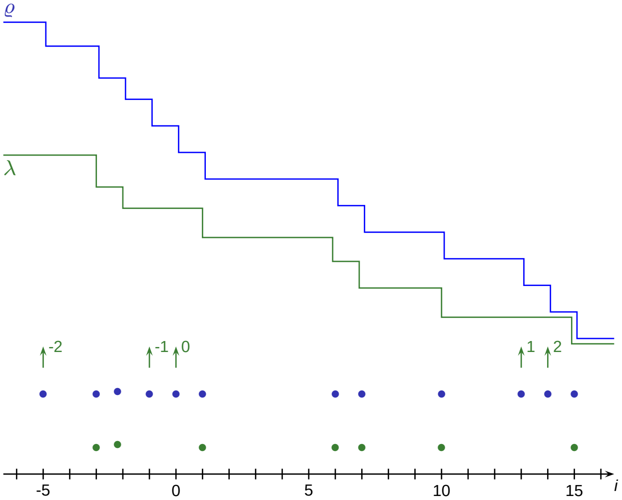

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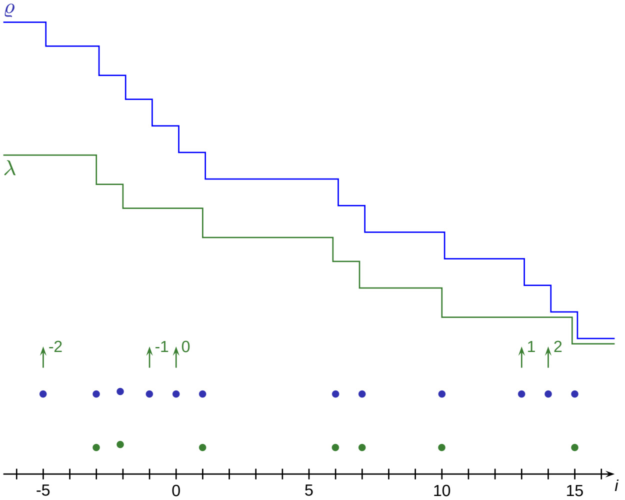

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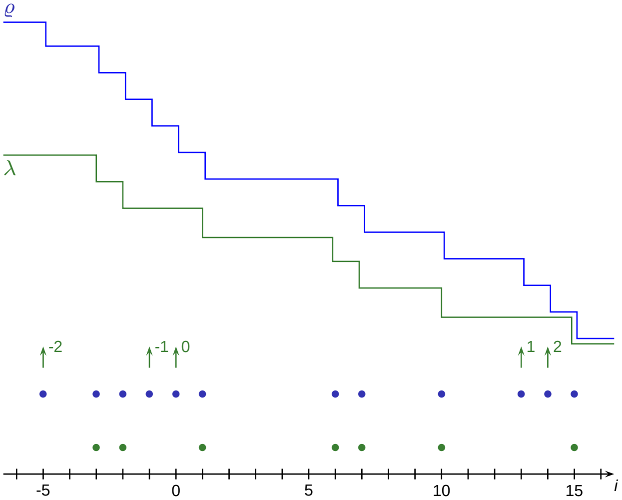

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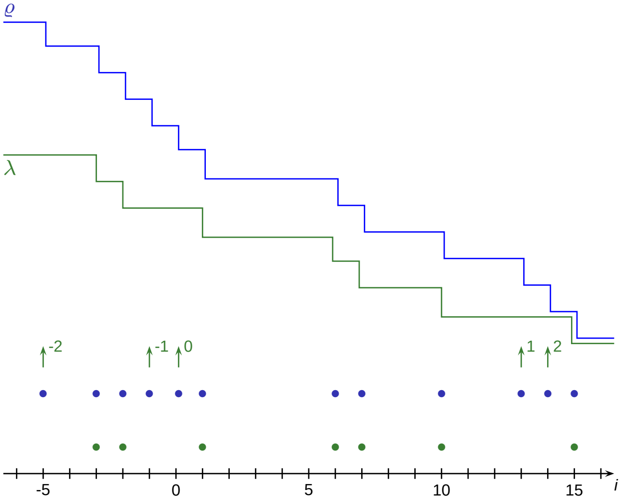

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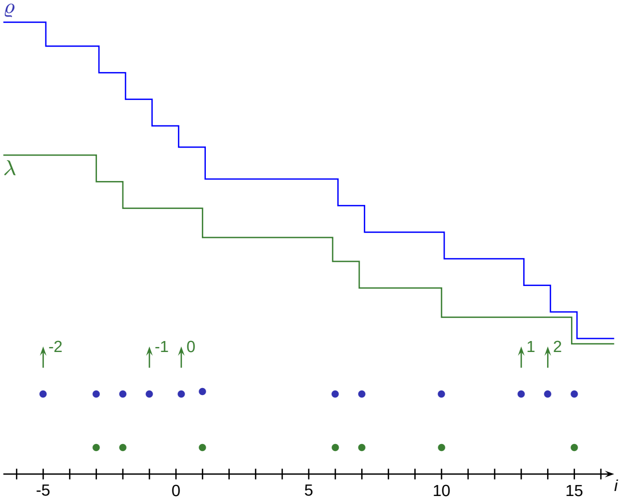

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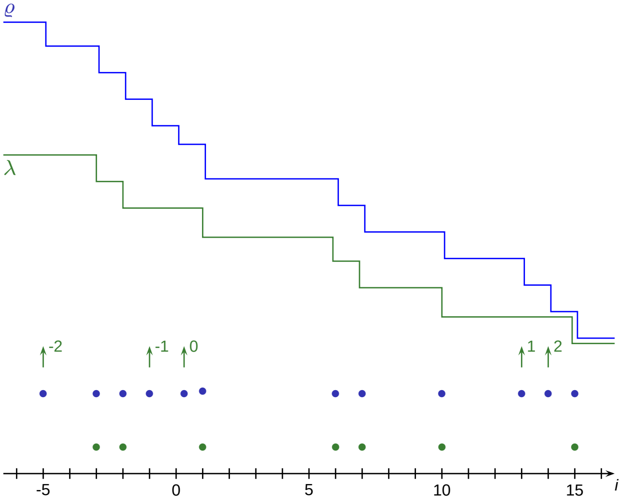

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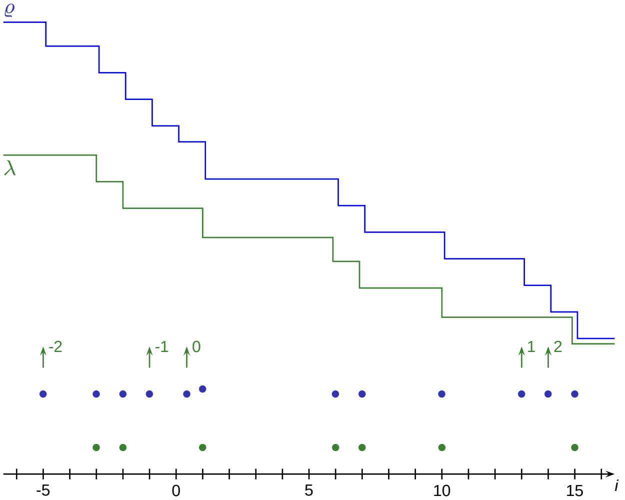

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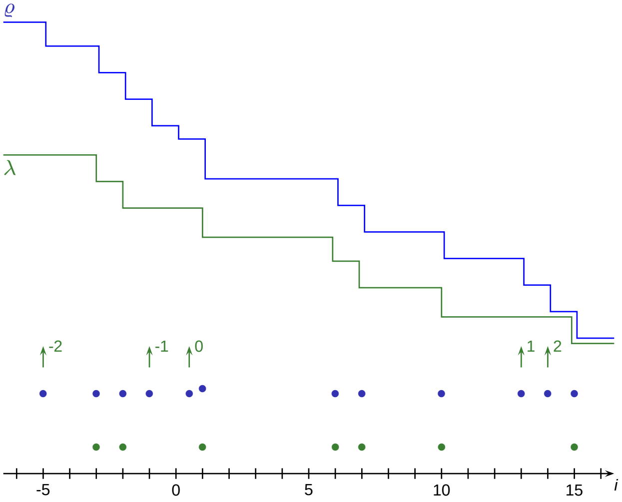

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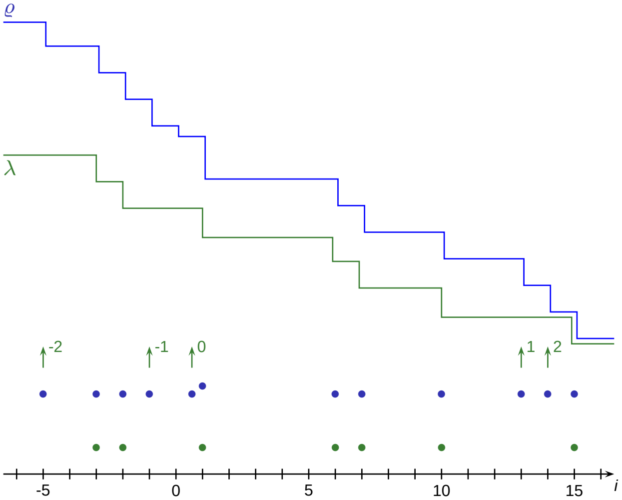

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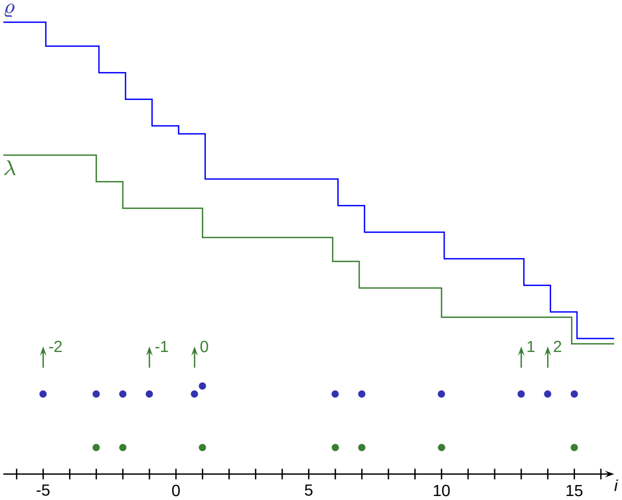

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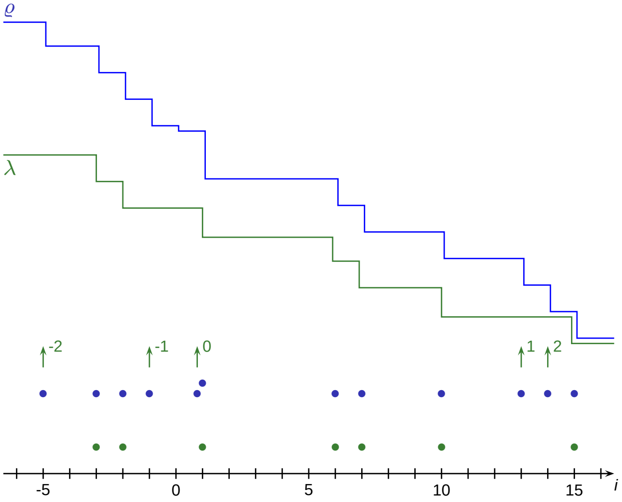

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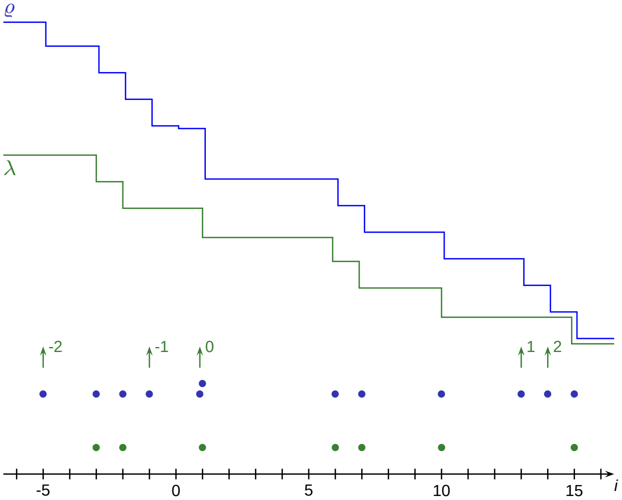

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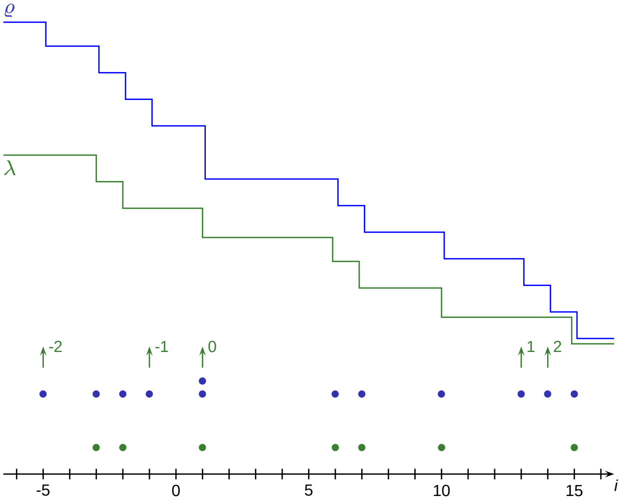

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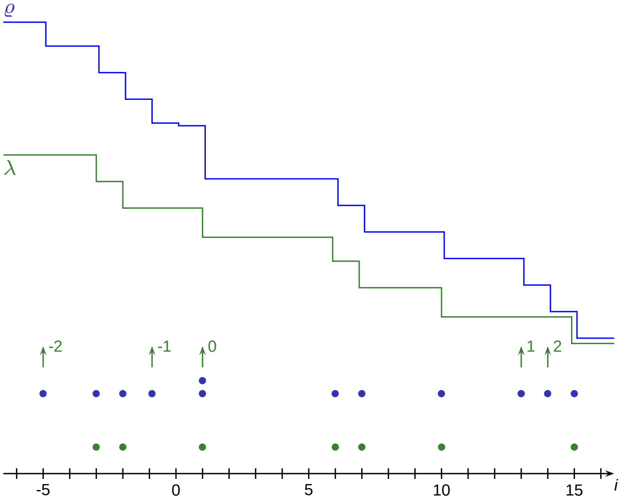

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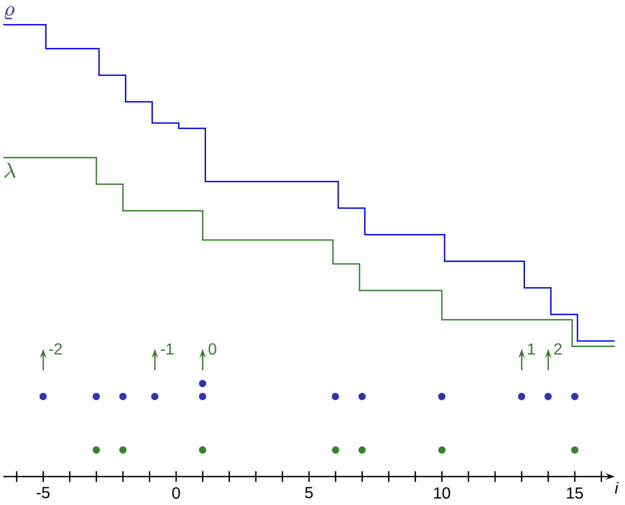

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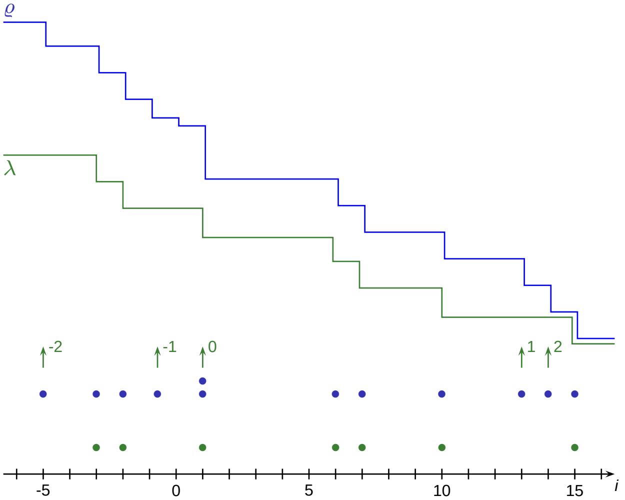

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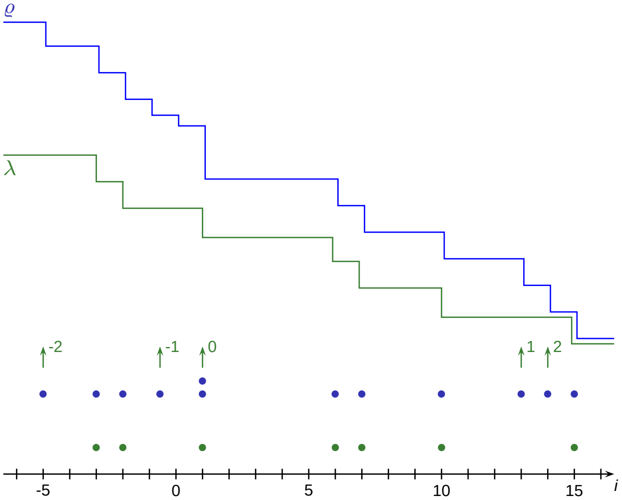

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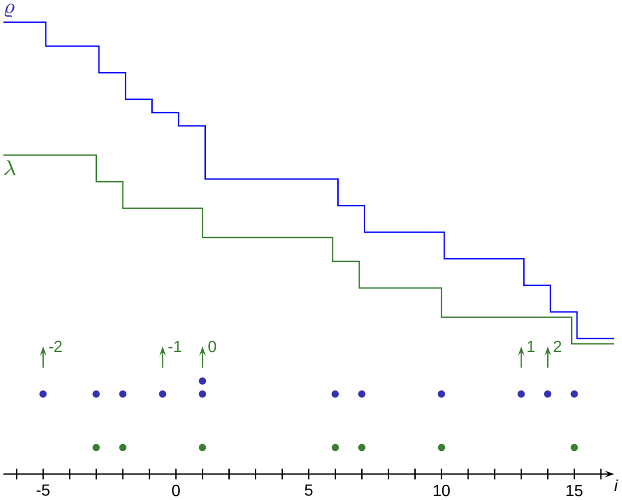

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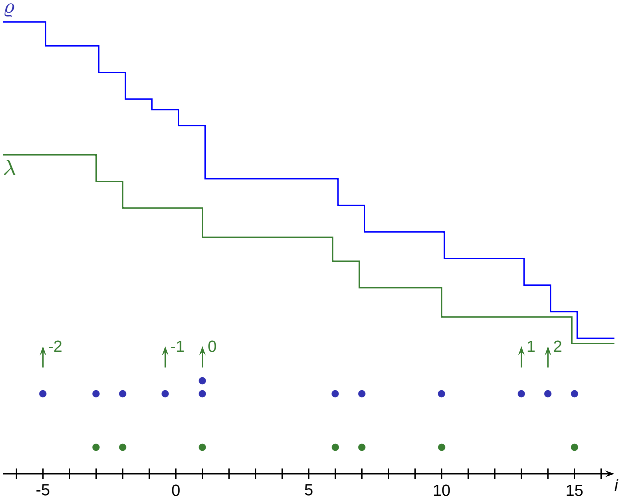

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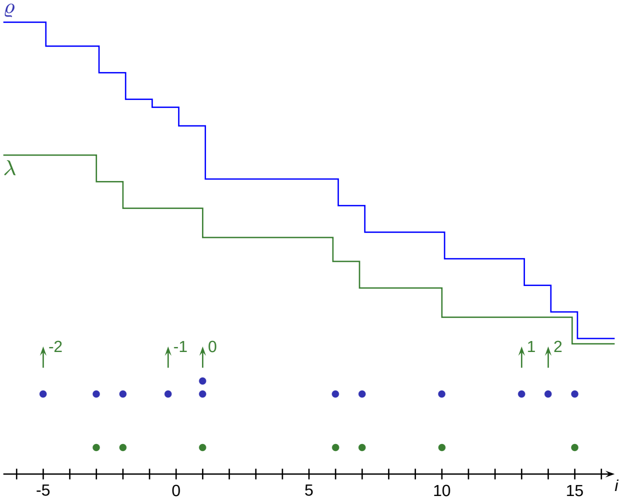

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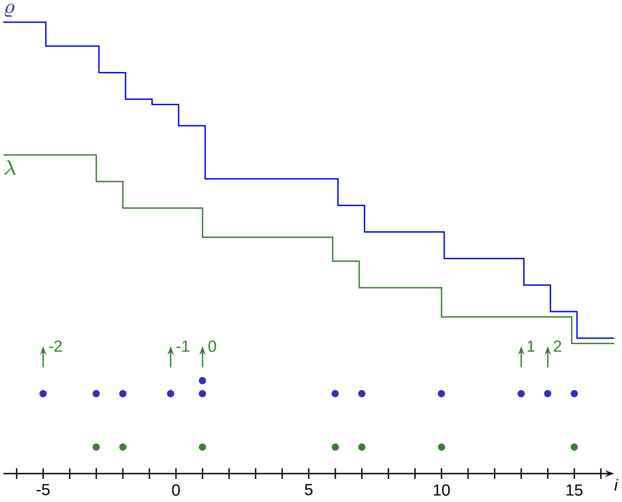

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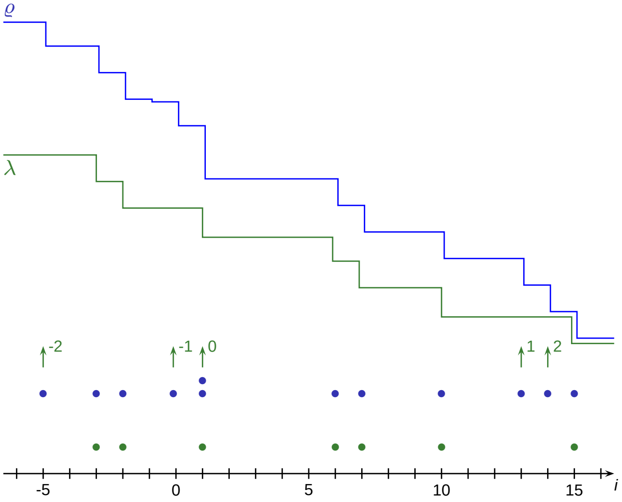

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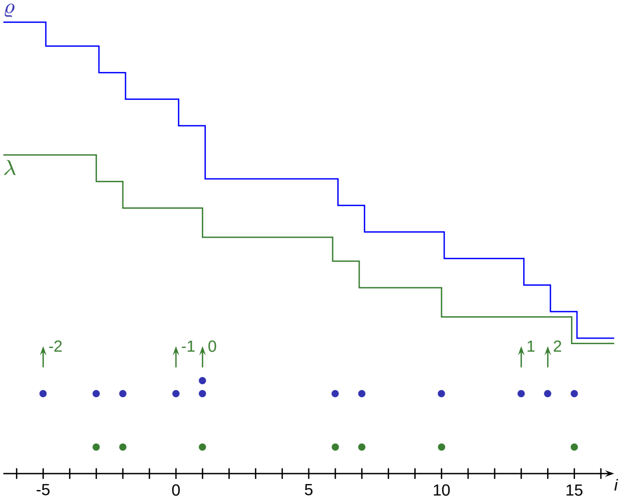

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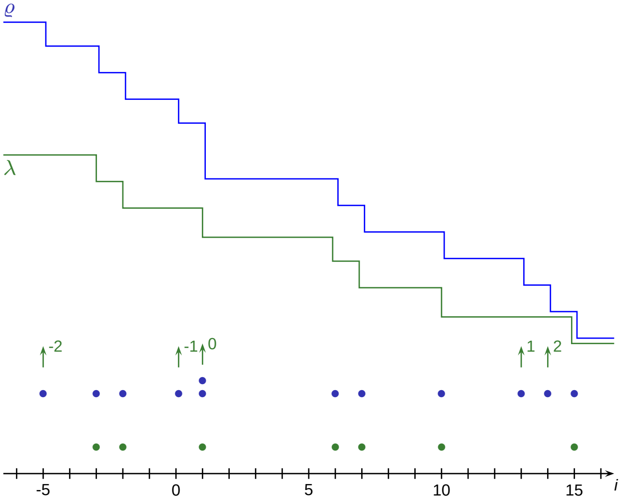

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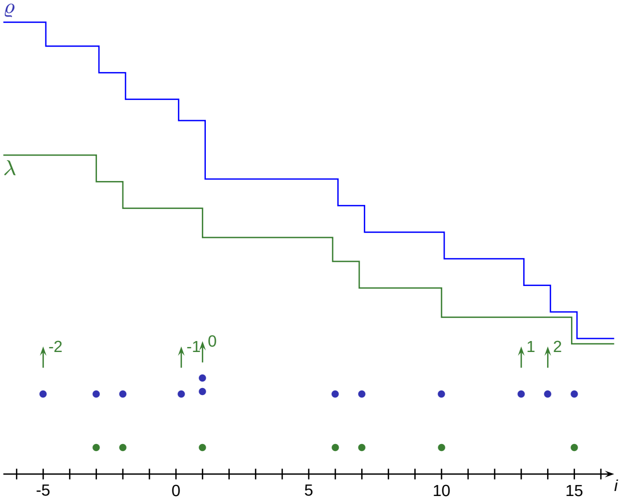

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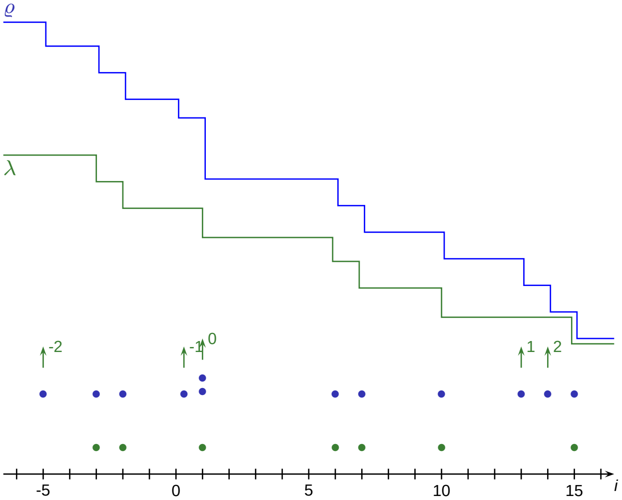

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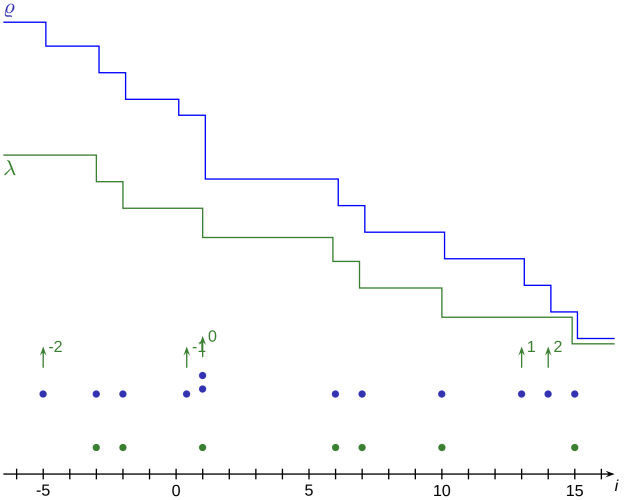

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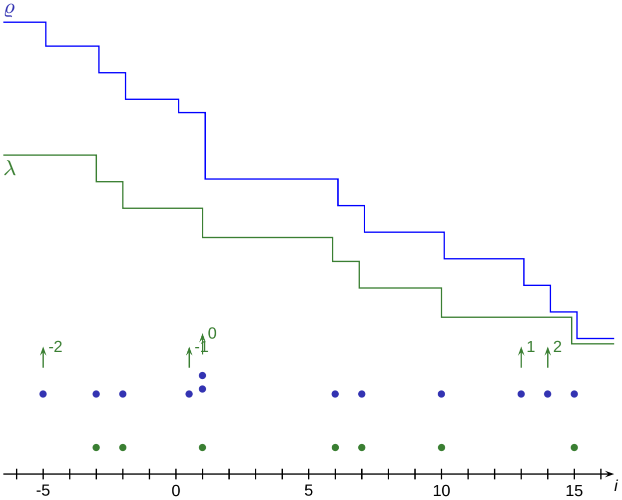

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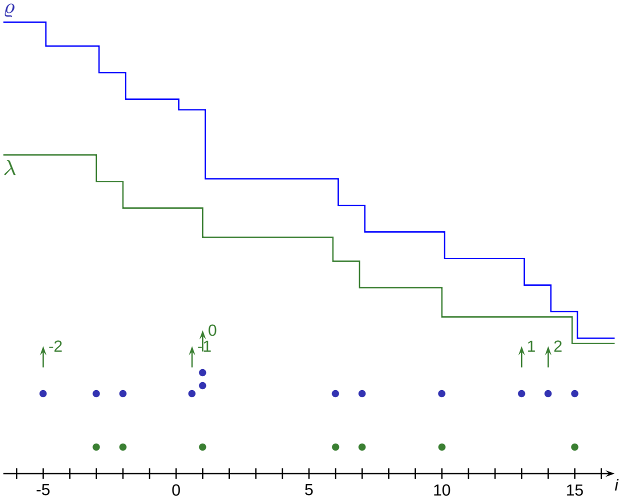

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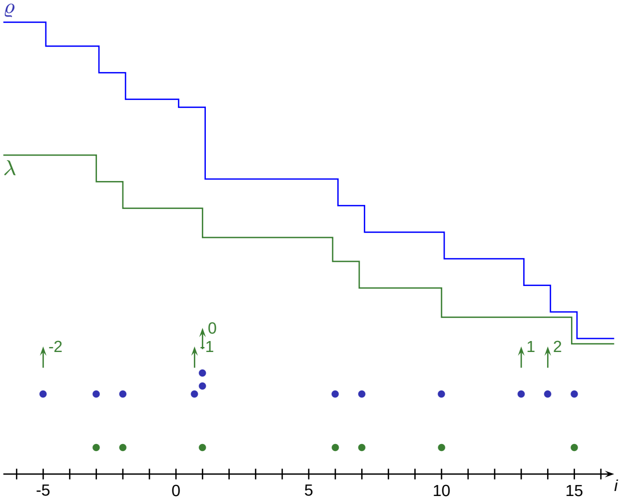

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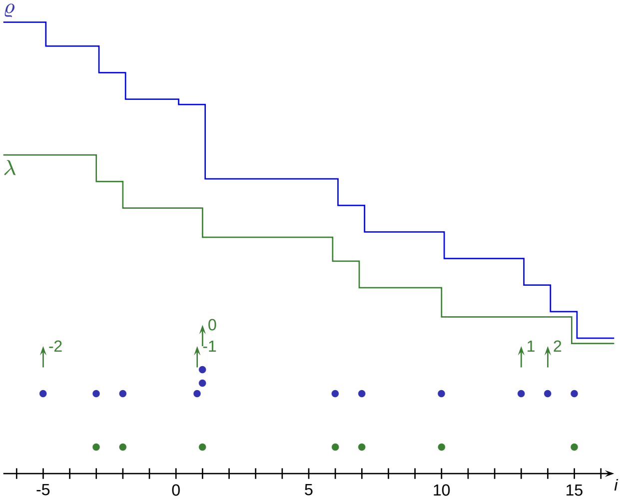

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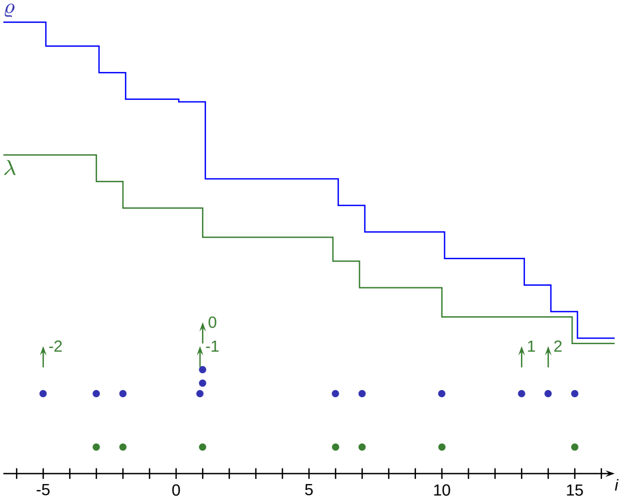

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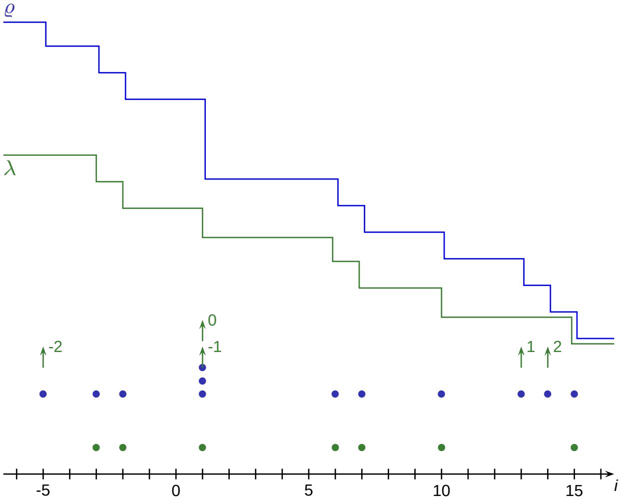

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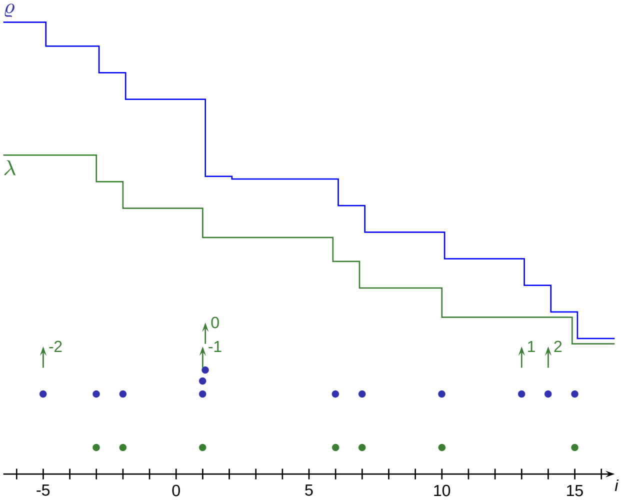

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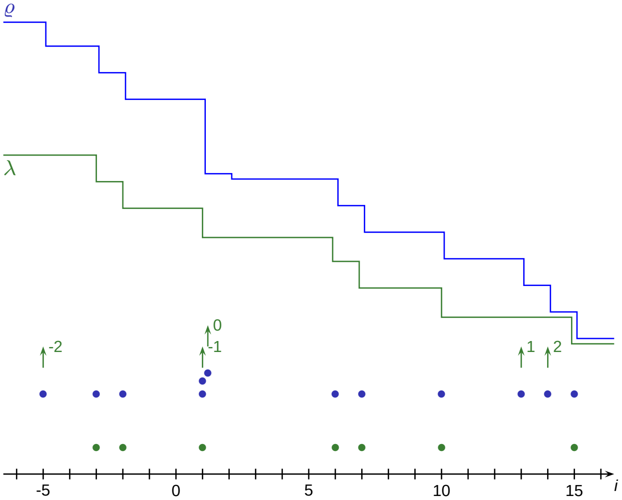

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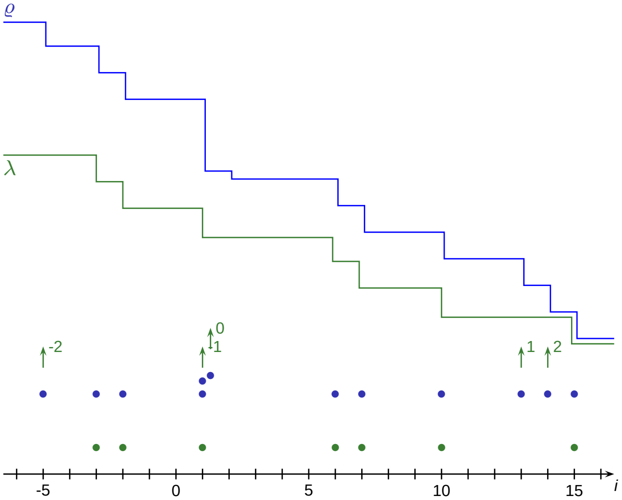

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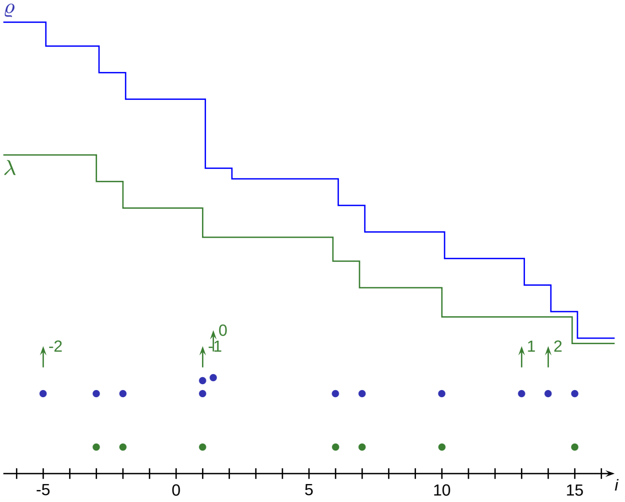

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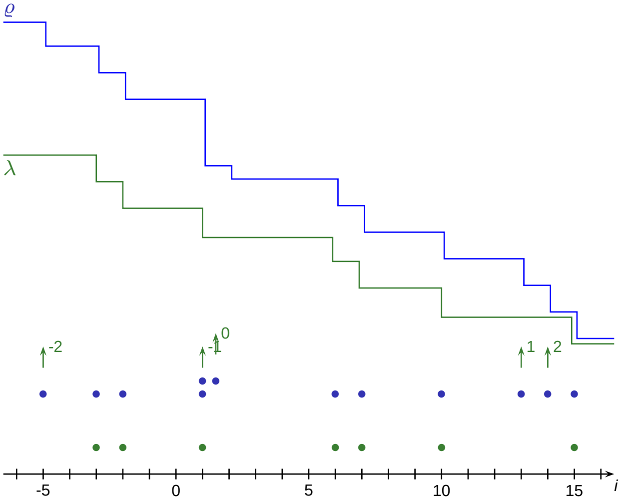

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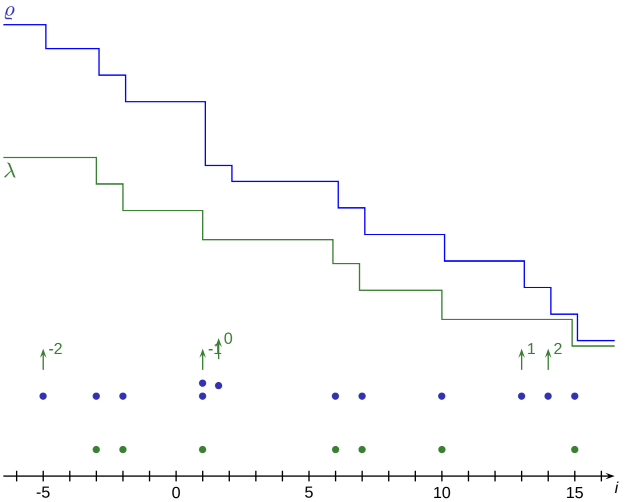

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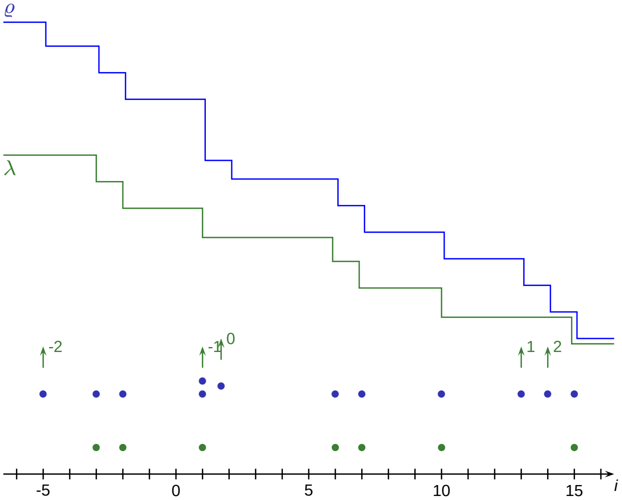

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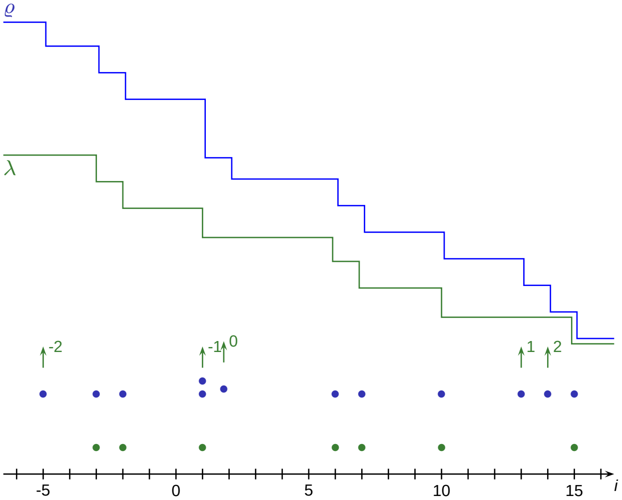

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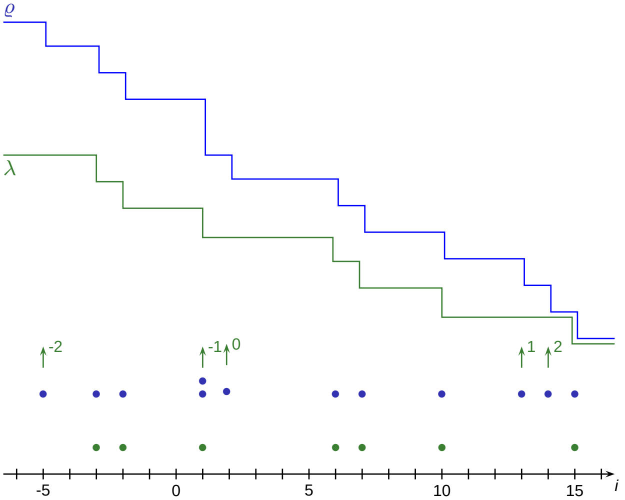

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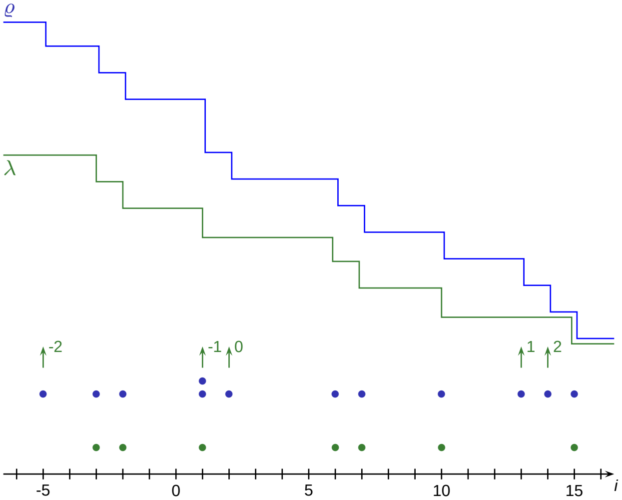

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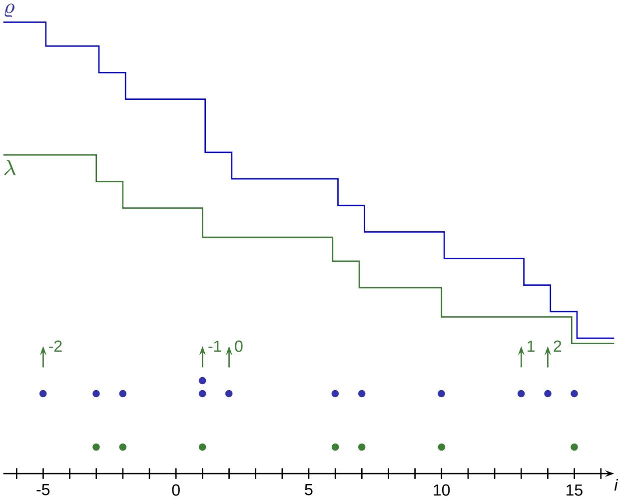
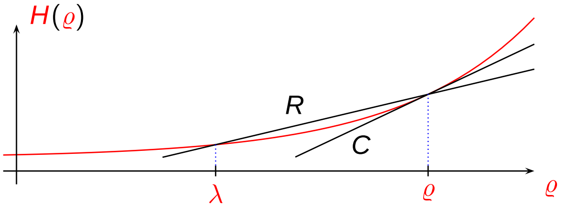


Picture:

The position $X(t)$ of $\uparrow^0$ follows the Rankine-Hugoniot speed R.

Characteristics (very briefly)

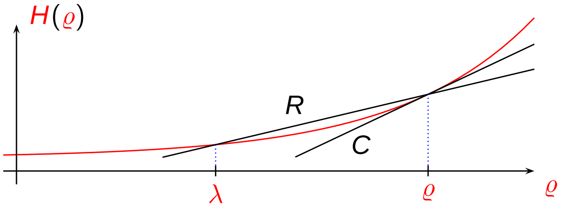
Convex flux (some cases of AZRP, ABLP):



Recall $$C = H'(\varrho) > R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}$$

Characteristics (very briefly)

Convex flux (some cases of AZRP, ABLP):

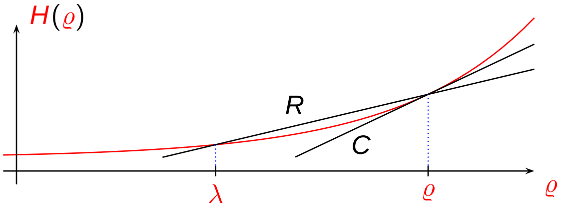


Recall $\quad C = H'(\varrho) > R = \dfrac{H(\varrho) - H(\lambda)}{\varrho - \lambda}$

Do we have $\quad Q(t) \overset{?}{\geq} X(t)$

Characteristics (very briefly)

Convex flux (some cases of AZRP, ABLP):

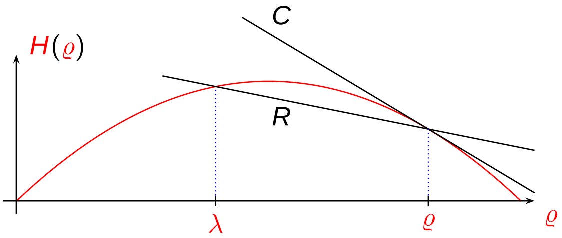


Recall $$C = H'(\varrho) > R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}$$

Do we have $$Q(t) \stackrel{?}{\geq} X(t) - \text{tight error}$$

Characteristics (very briefly)

Concave flux (ASEP, AZRP):



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Characteristics (very briefly)

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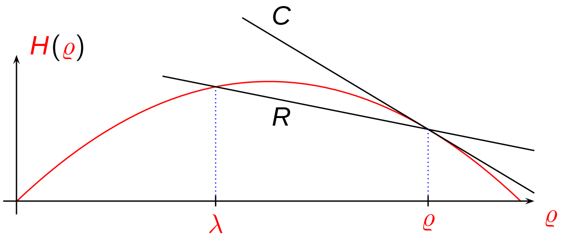
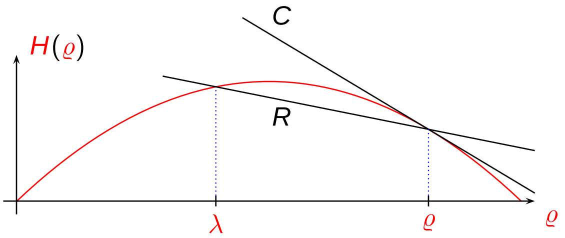


$$C = H'(\varrho) < R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}$$

Do we have $\quad Q(t) \overset{?}{\leq} X(t)$

Characteristics (very briefly)

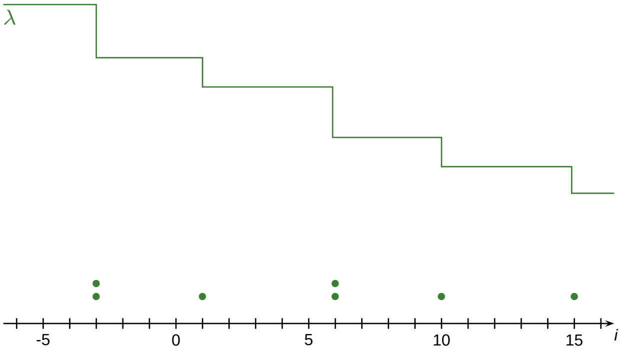
Concave flux (ASEP, AZRP):



$$C = H'(\varrho) < R = \frac{H(\varrho) - H(\lambda)}{\varrho - \lambda}$$

Do we have $\quad Q(t) \overset{?}{\leq} X(t) +$ tight error

Many second class particles



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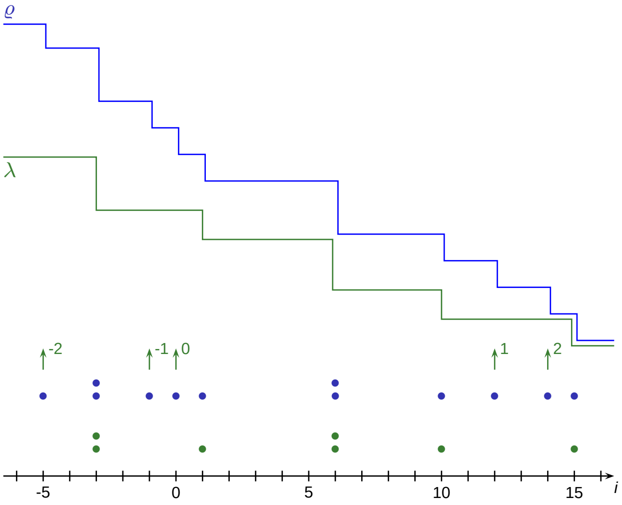
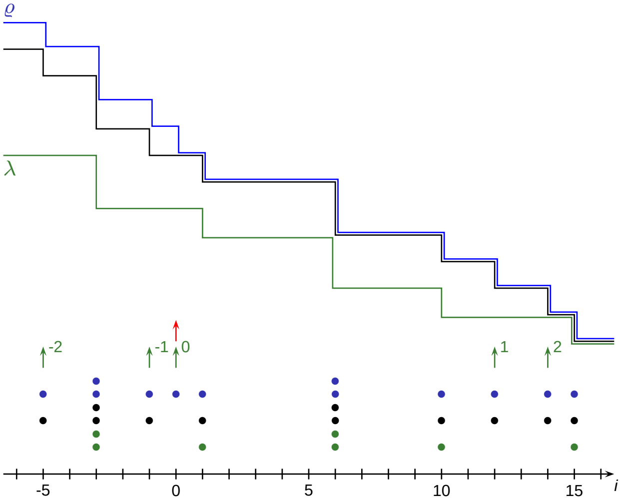
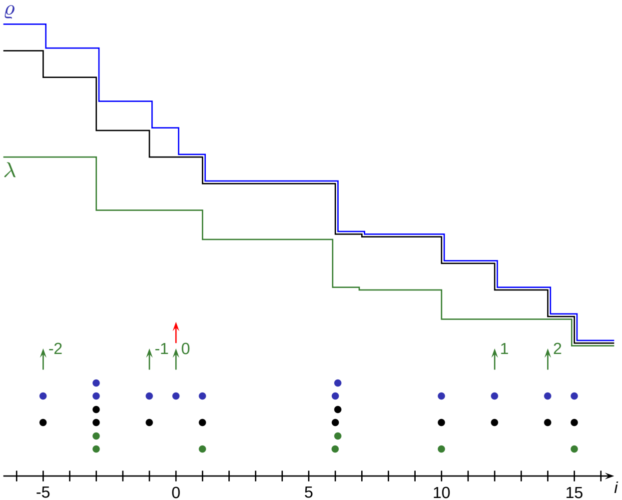


Many second class particles plus one



Couple three processes, and $X(t)$ to $Q(t)$.

Many second class particles plus one



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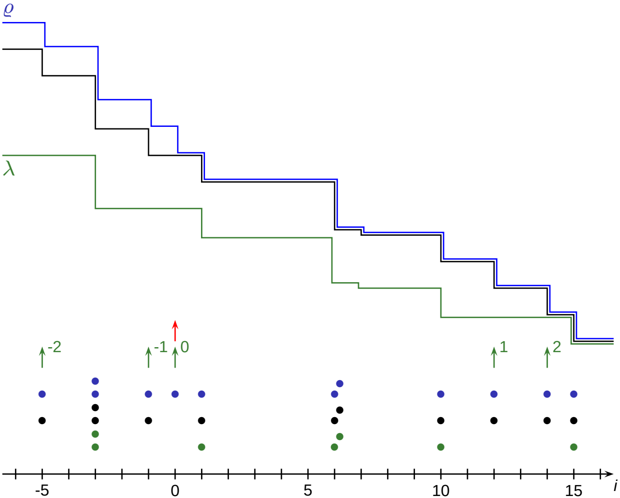

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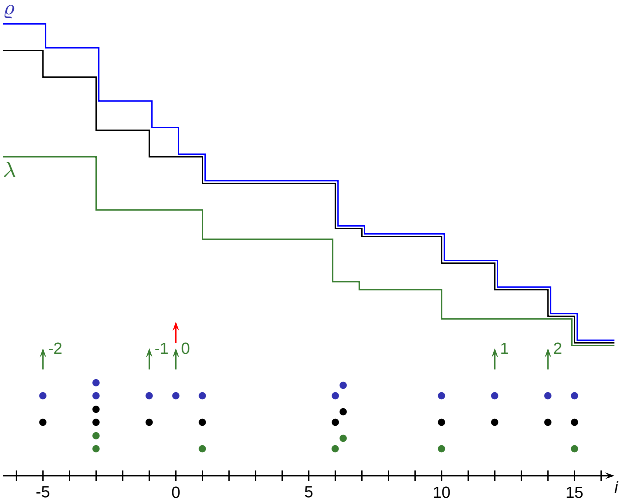

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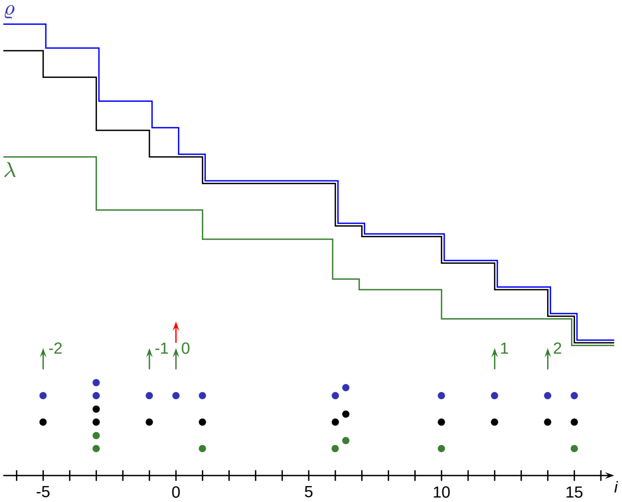

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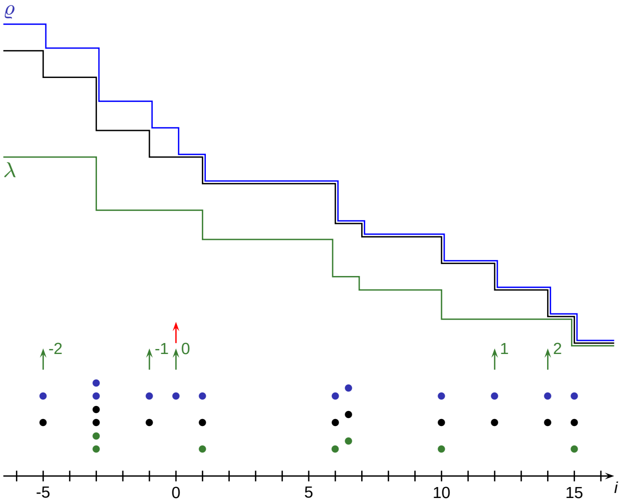

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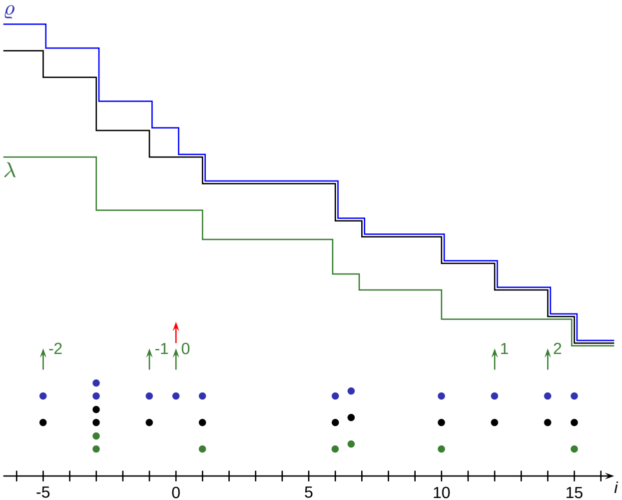

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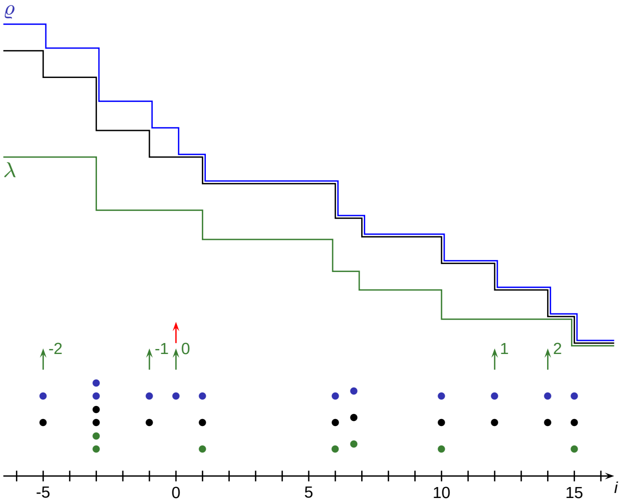

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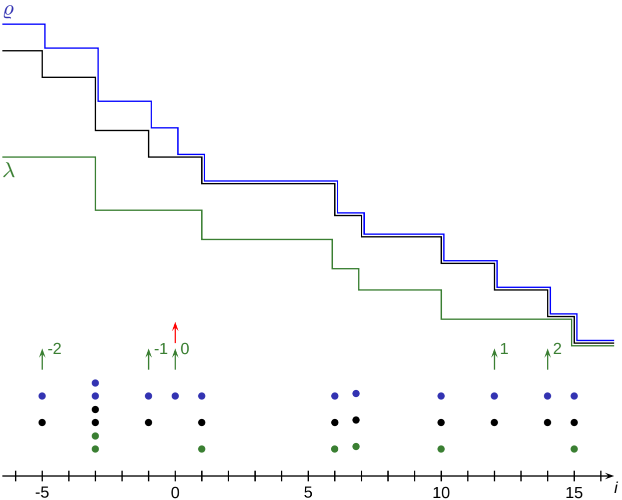

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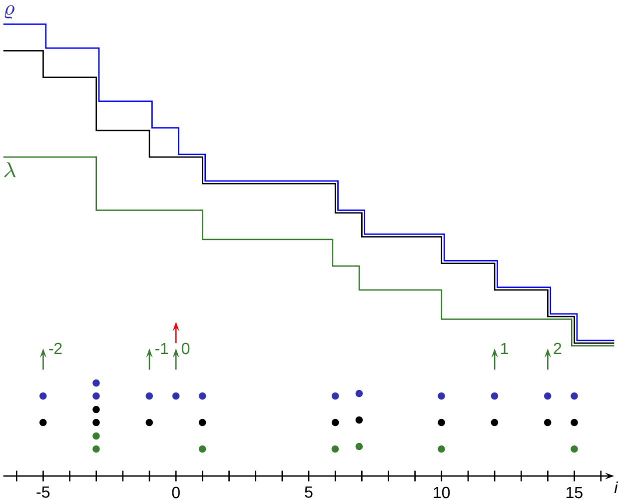

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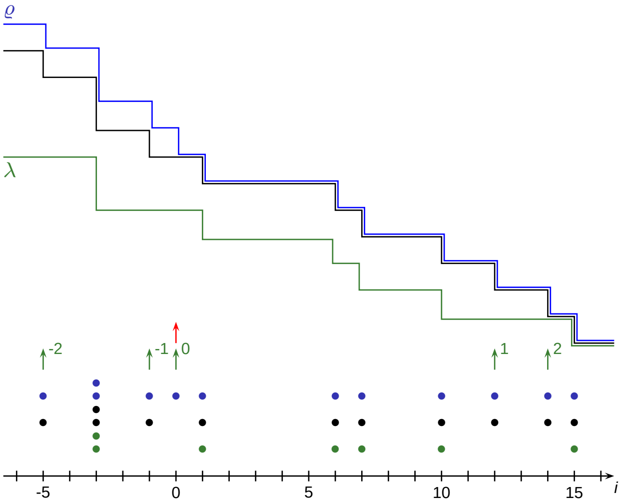

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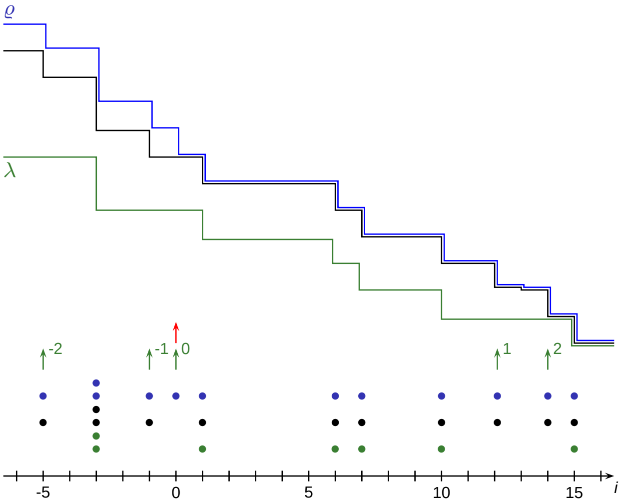

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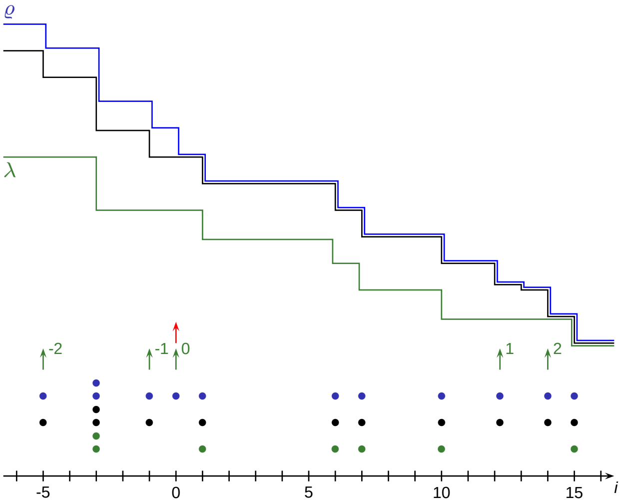

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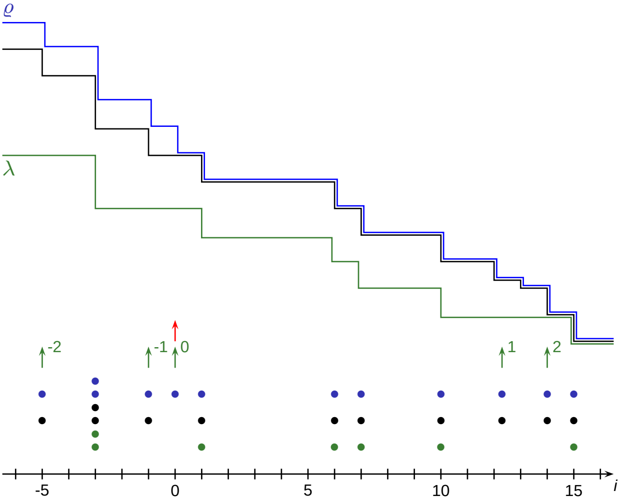

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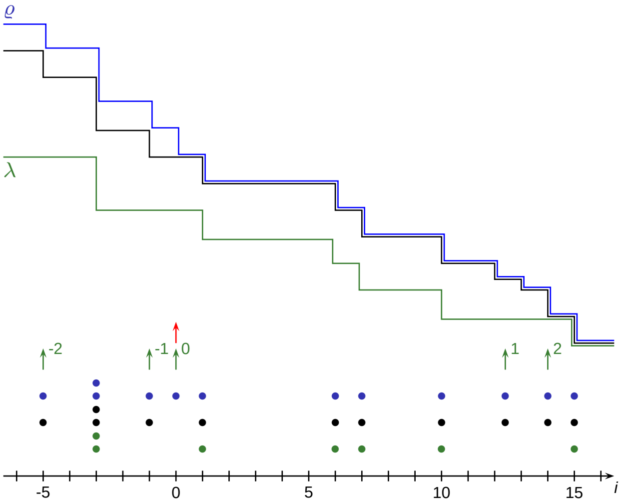

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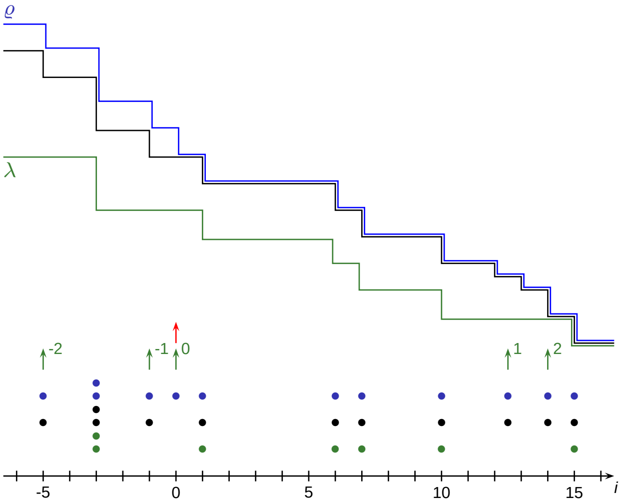

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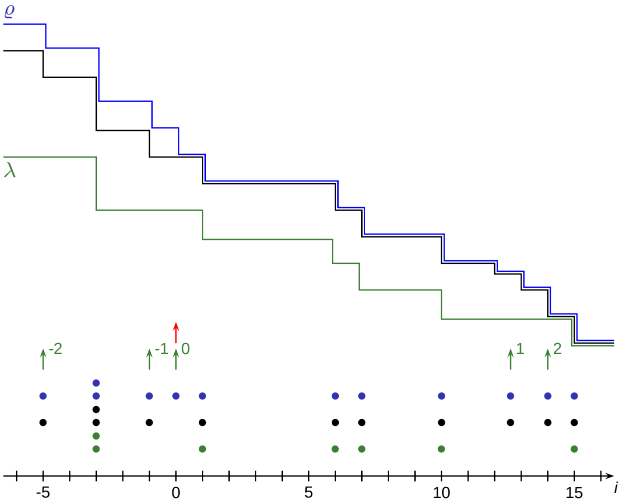

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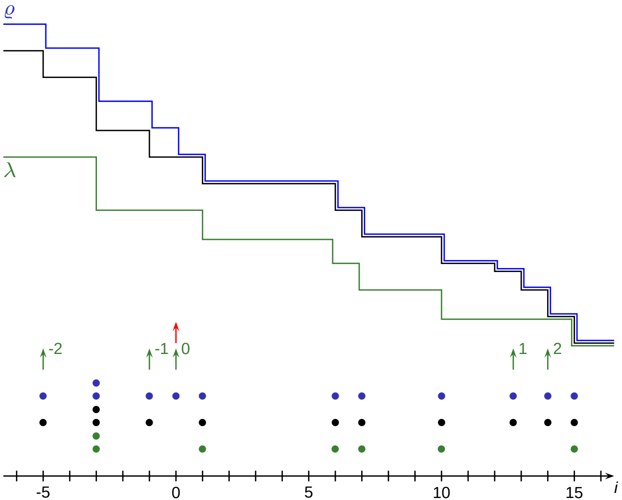

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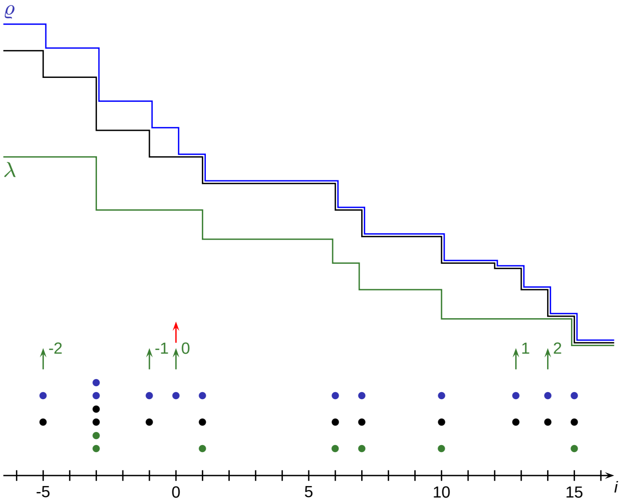

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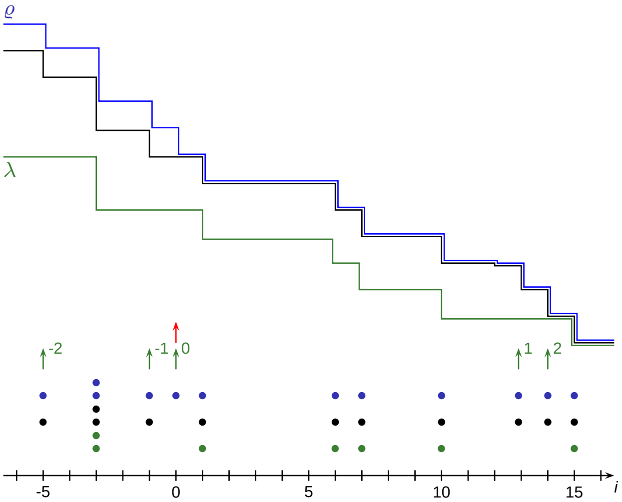

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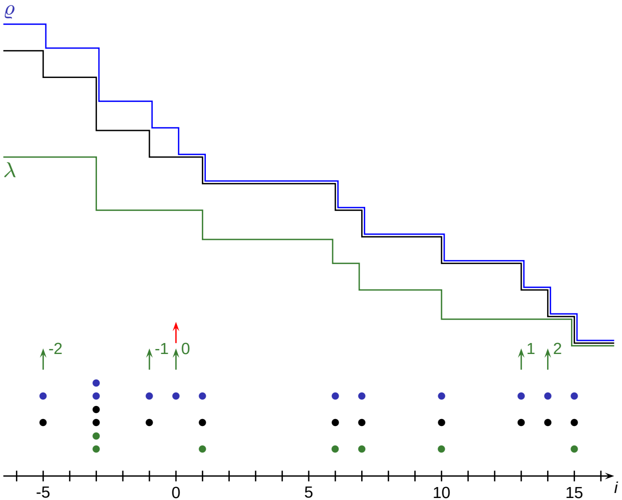

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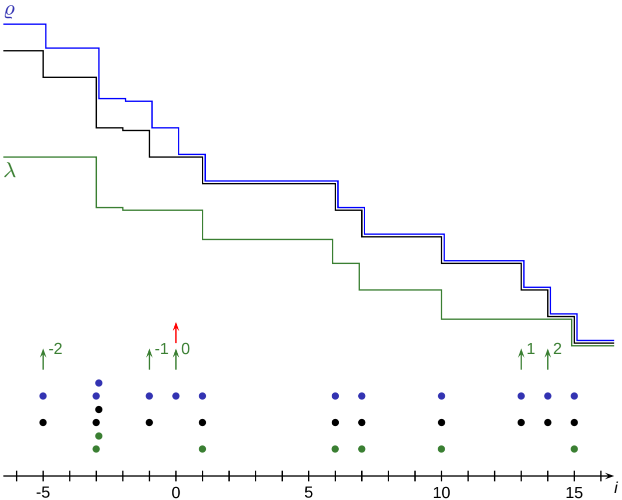

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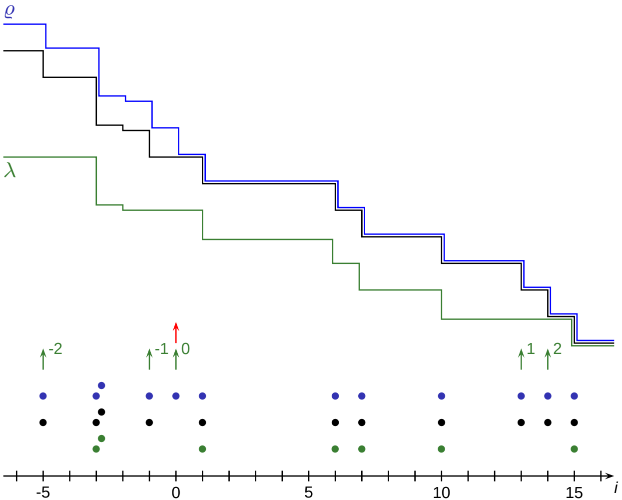

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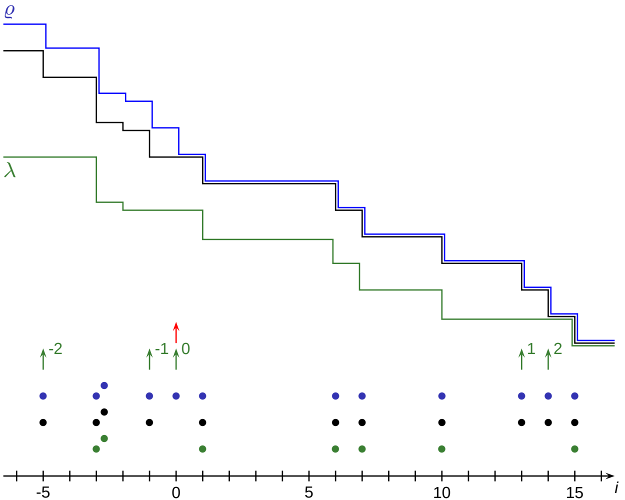

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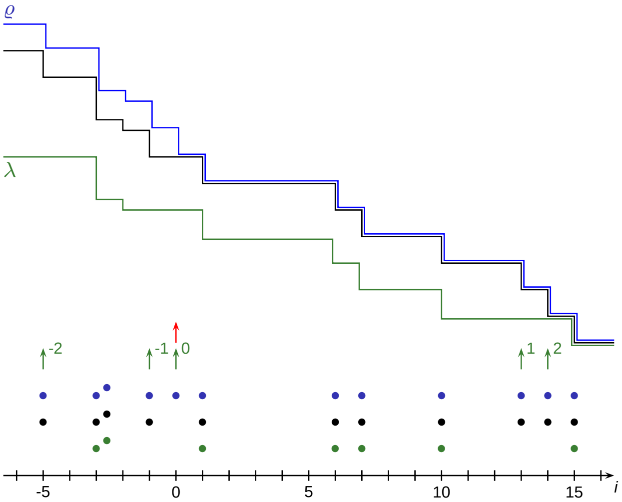

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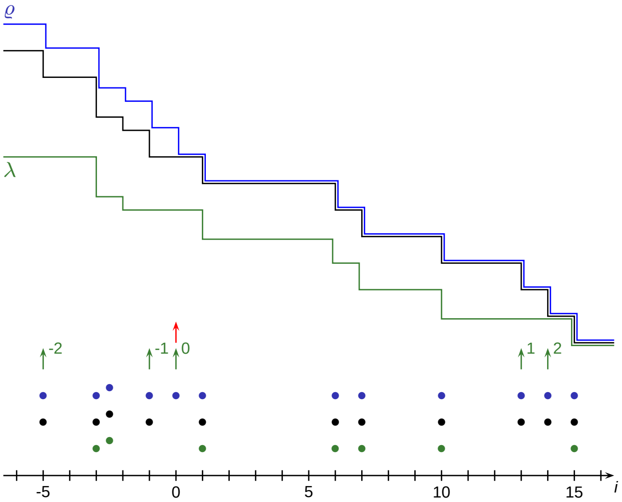

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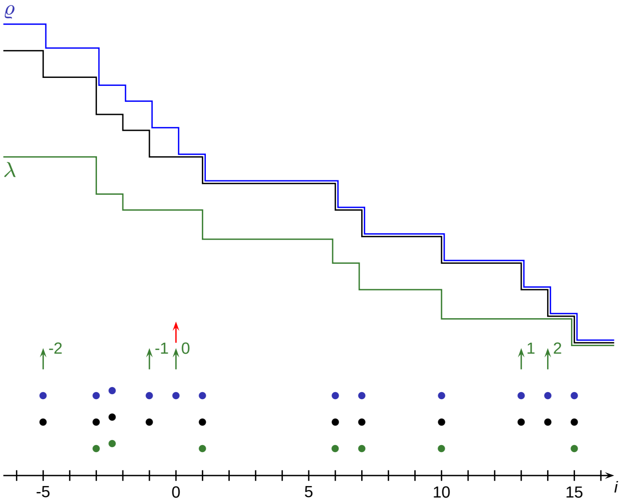

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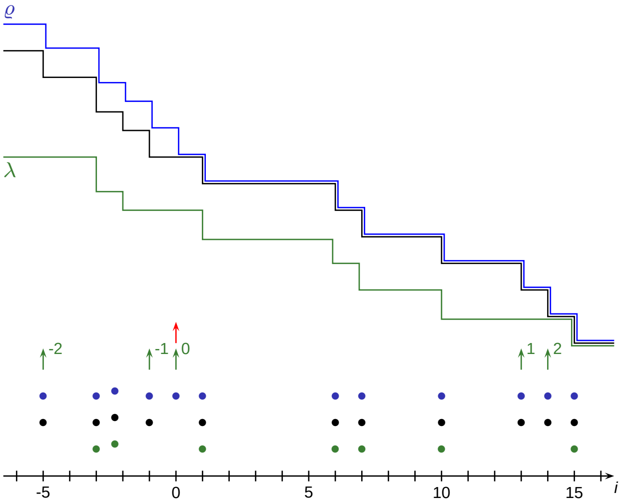

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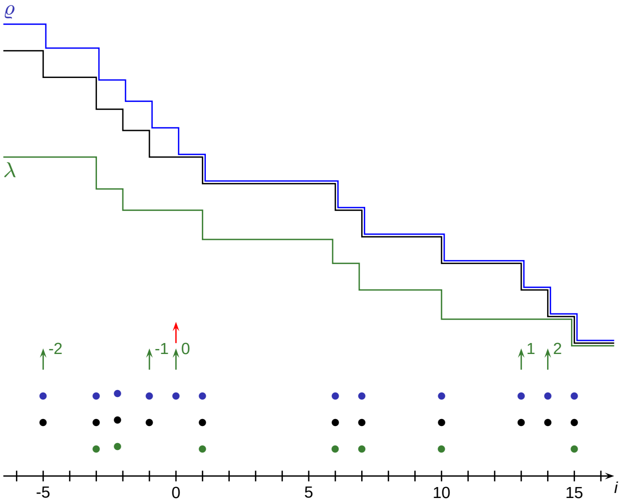

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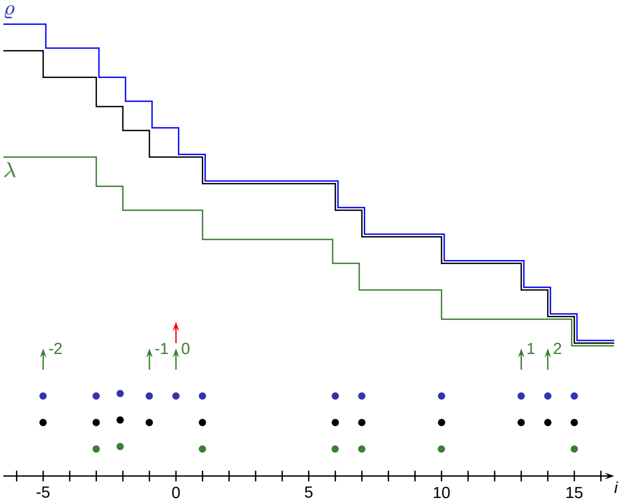

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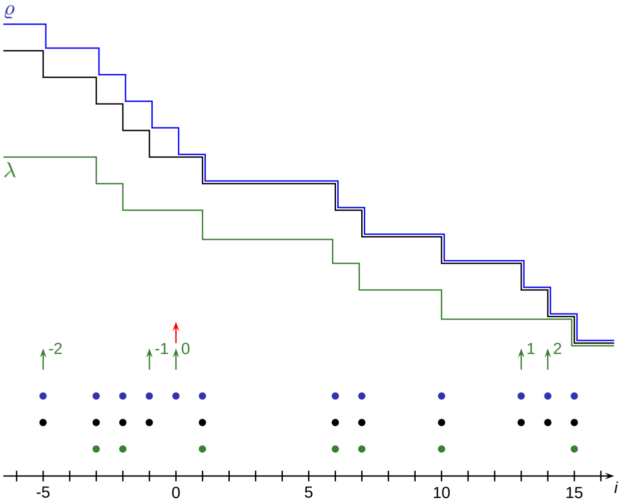

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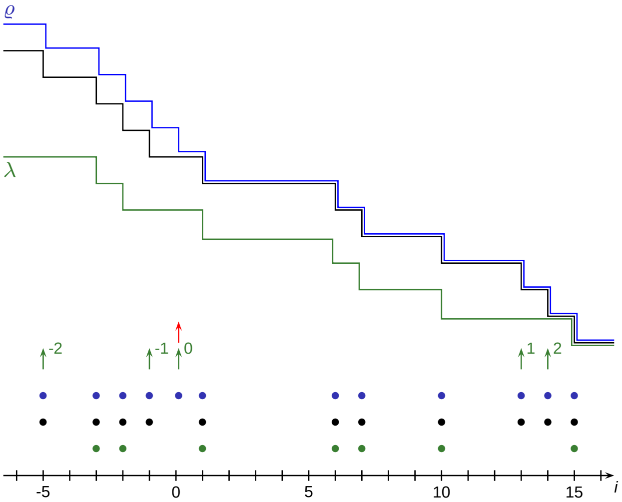

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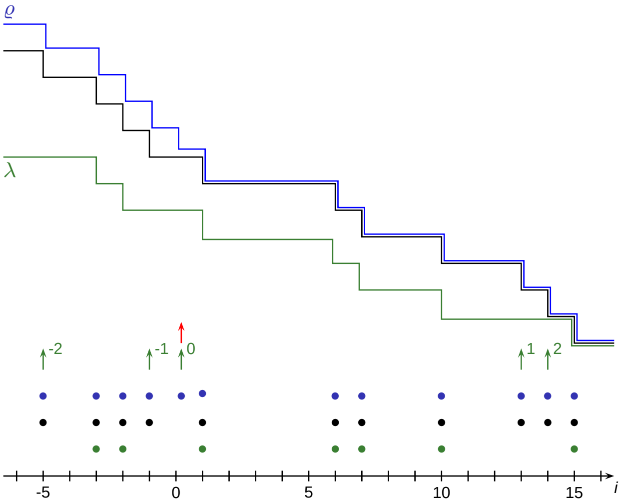

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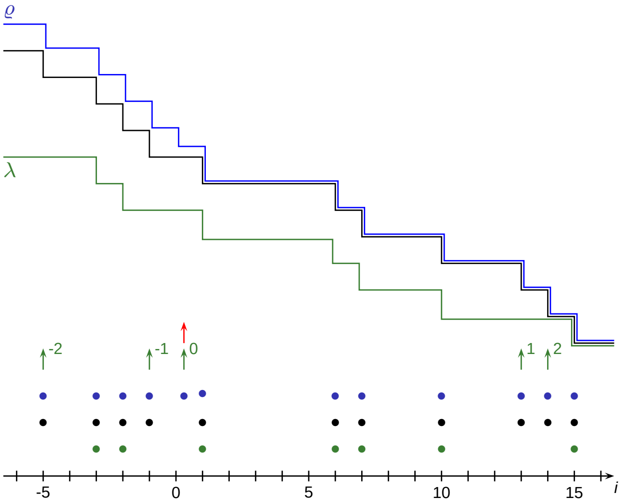

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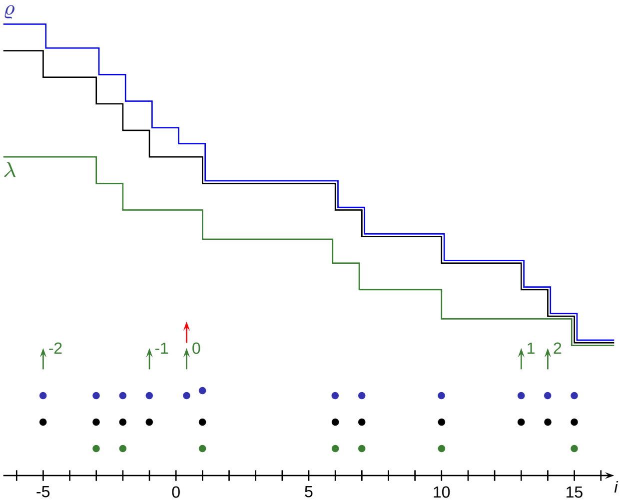

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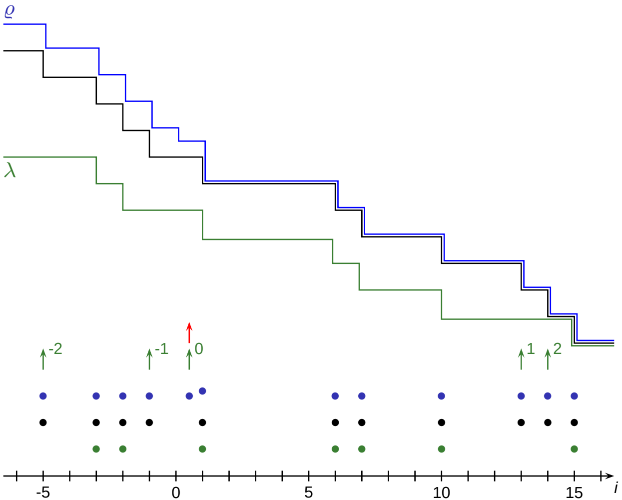

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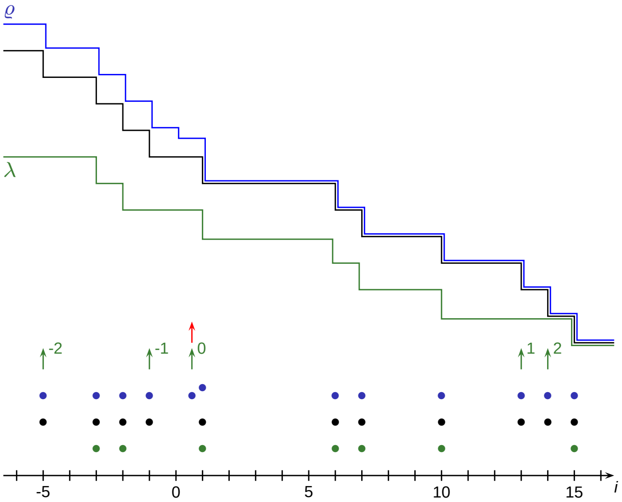

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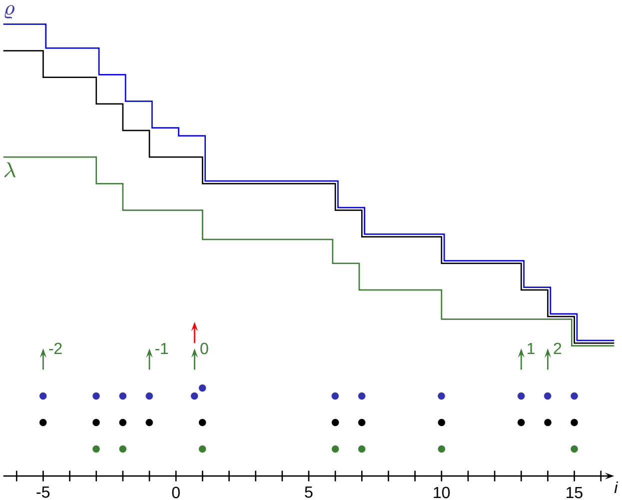

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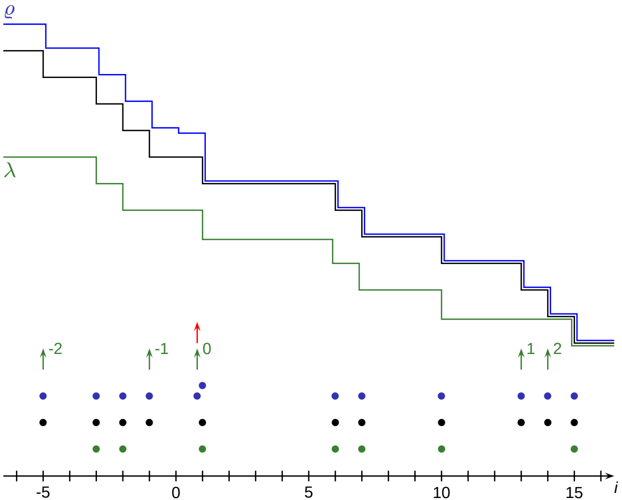

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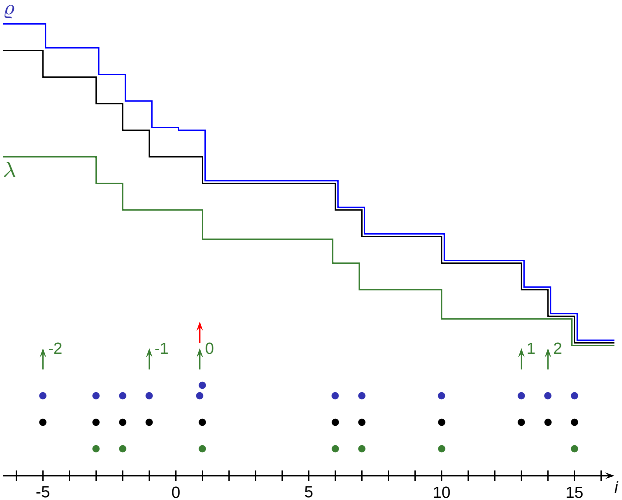

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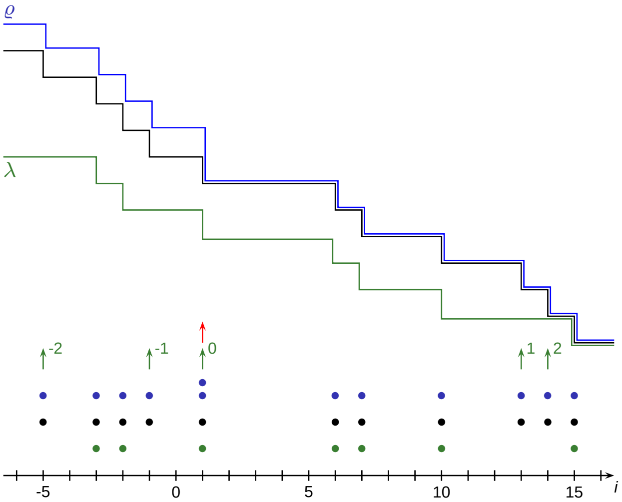

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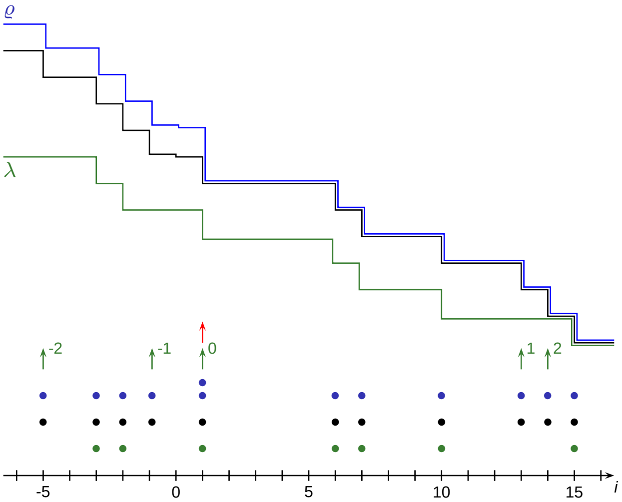

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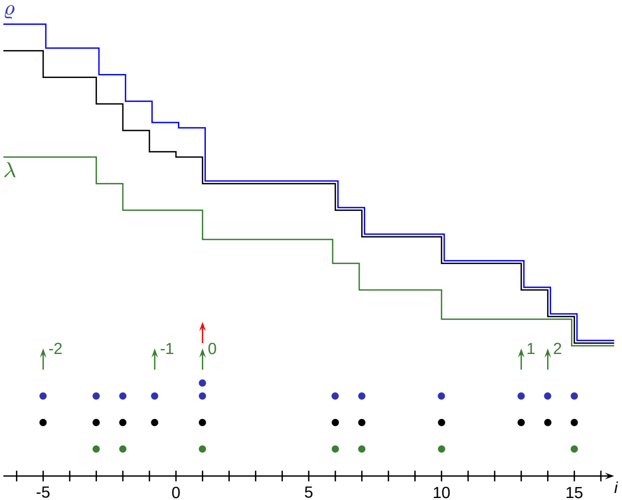

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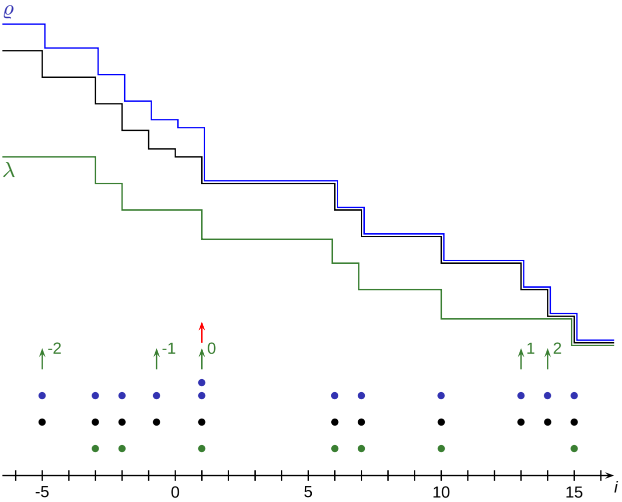

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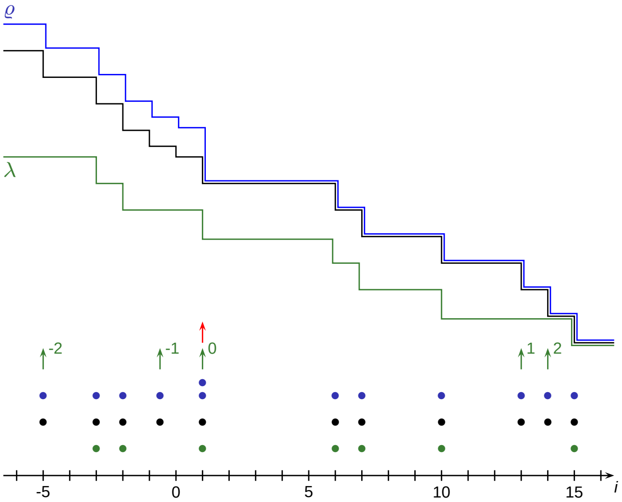

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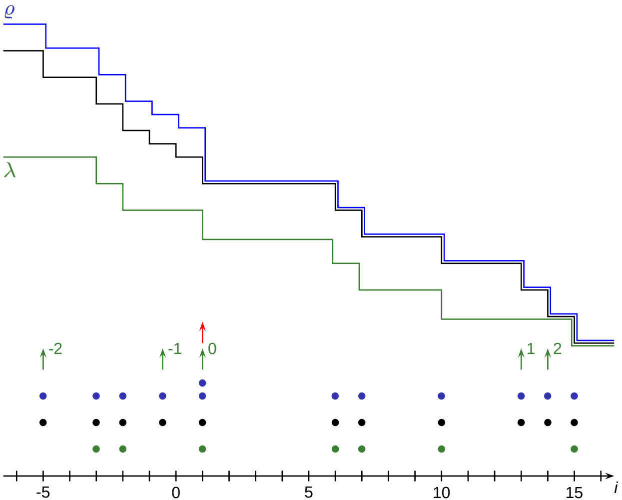

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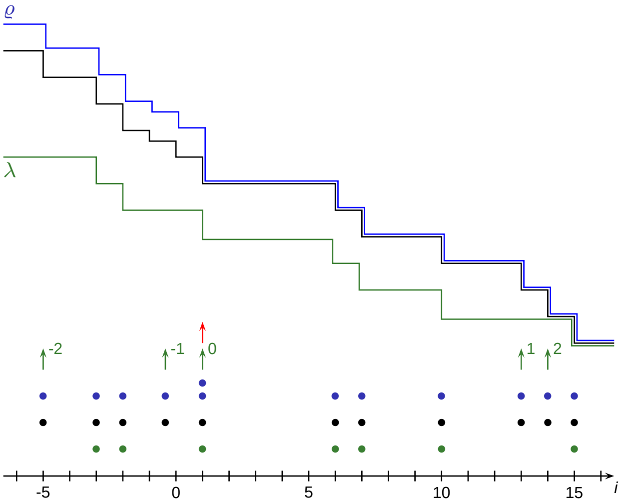

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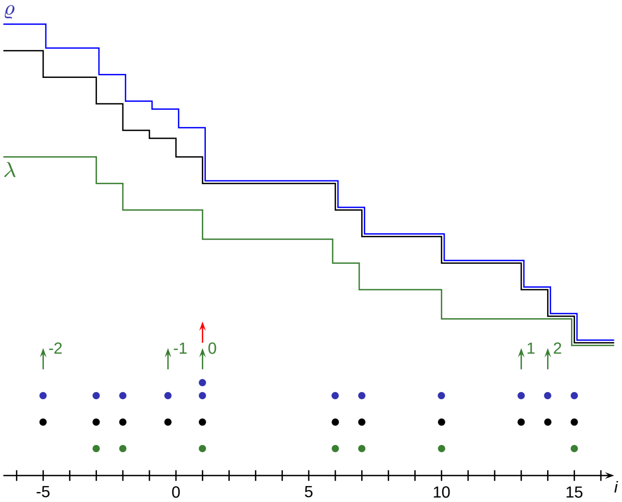

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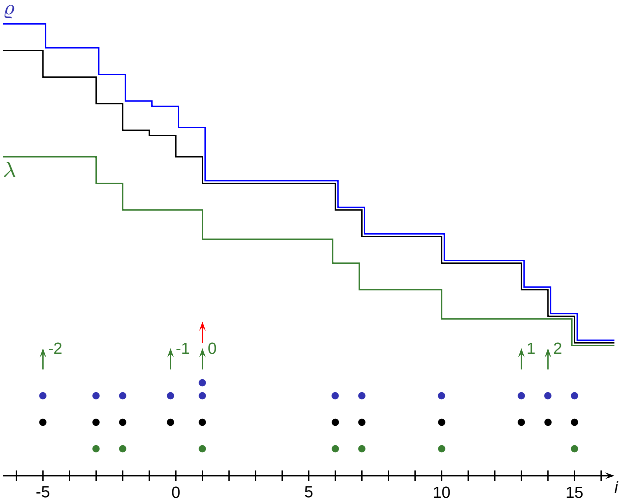

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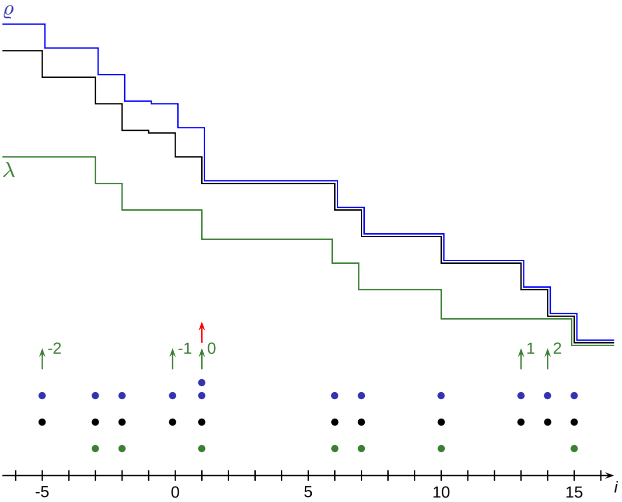

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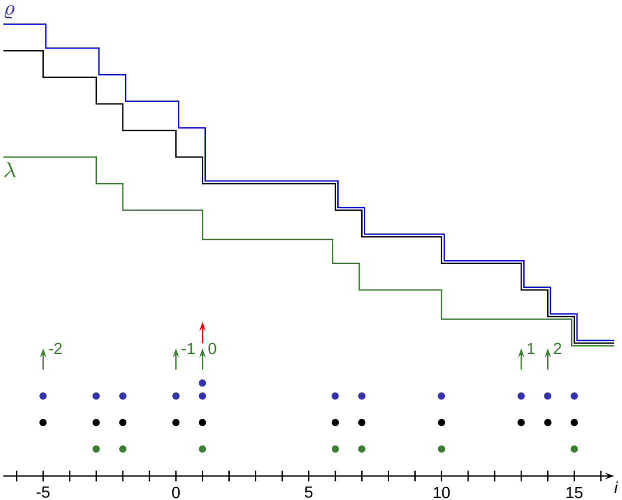

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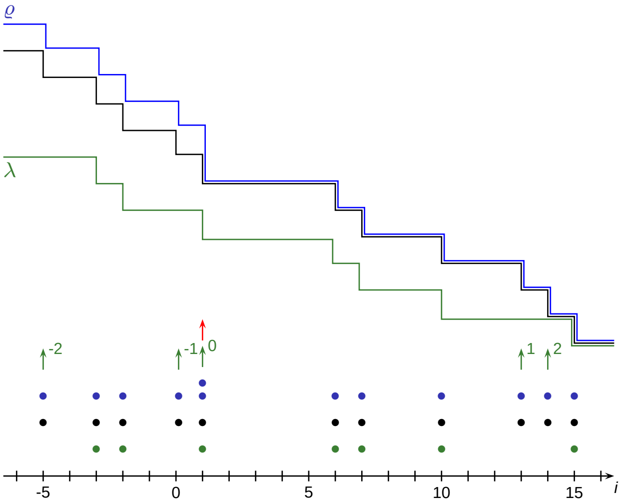

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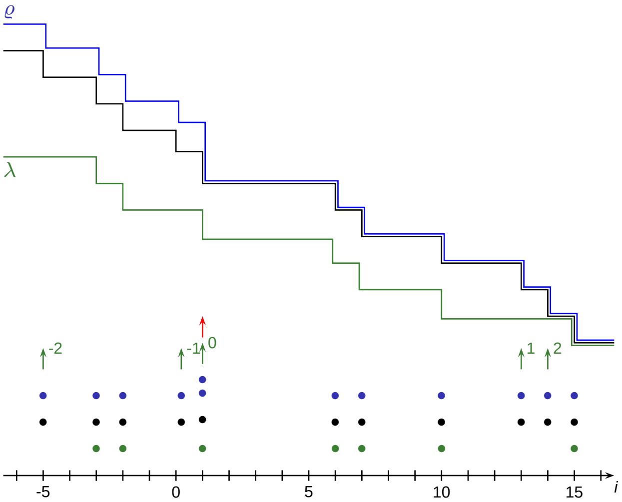

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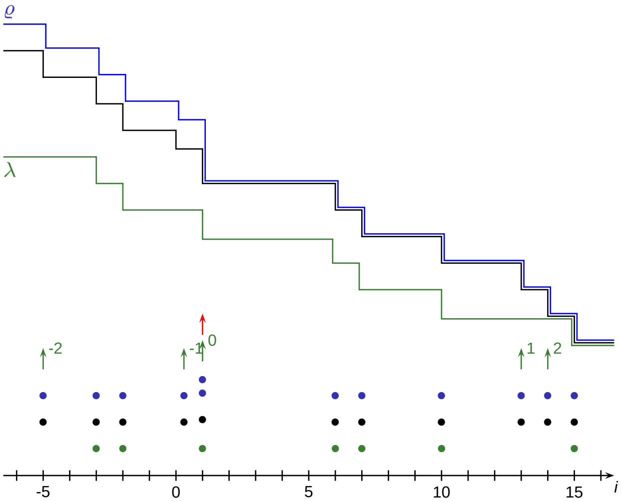

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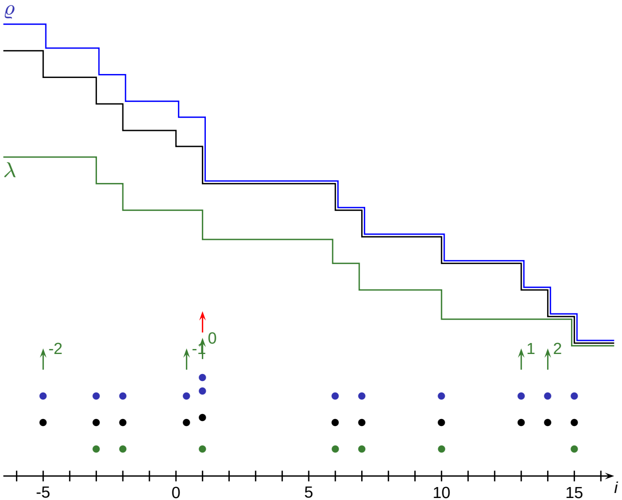

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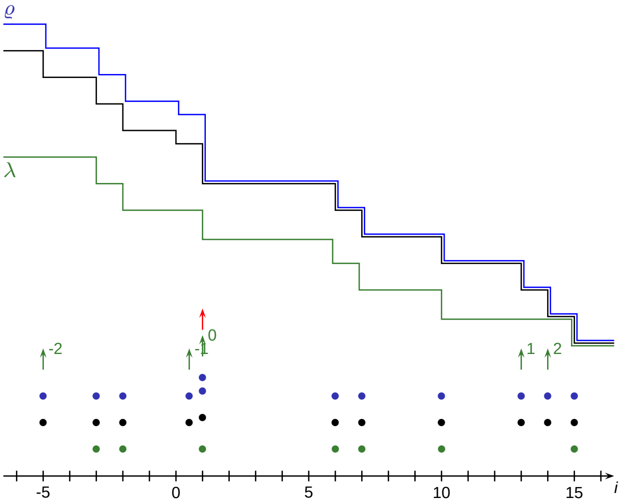

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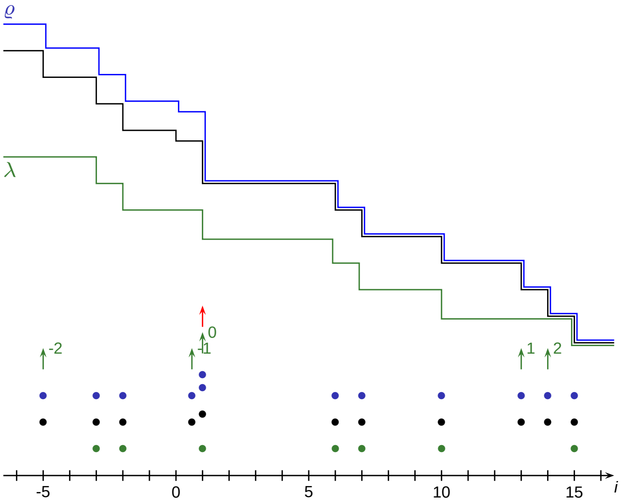

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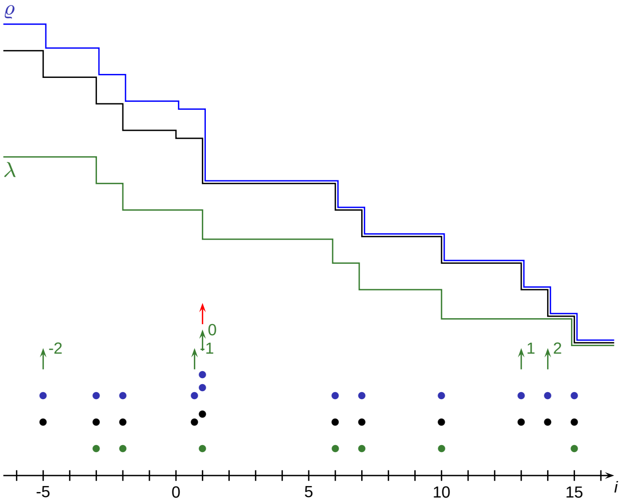

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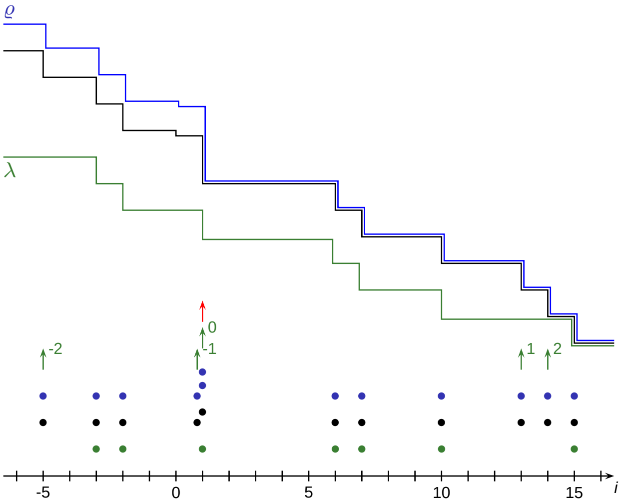

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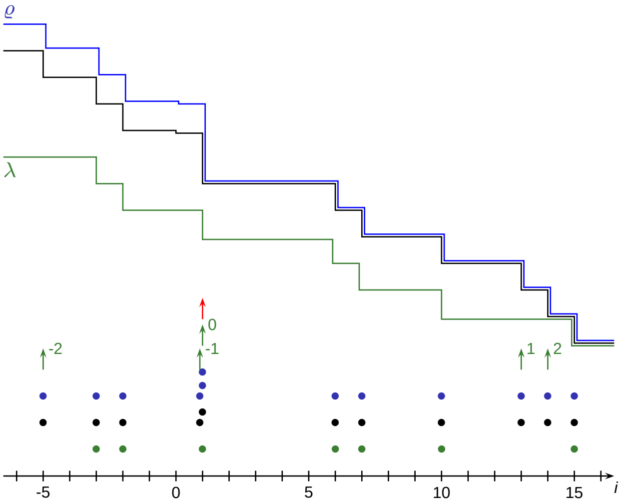

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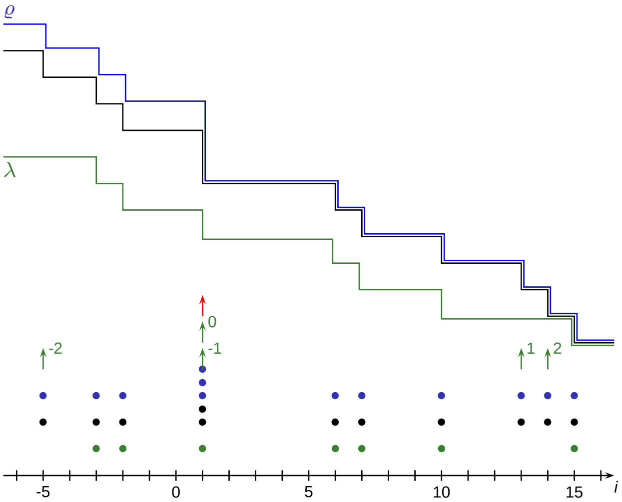

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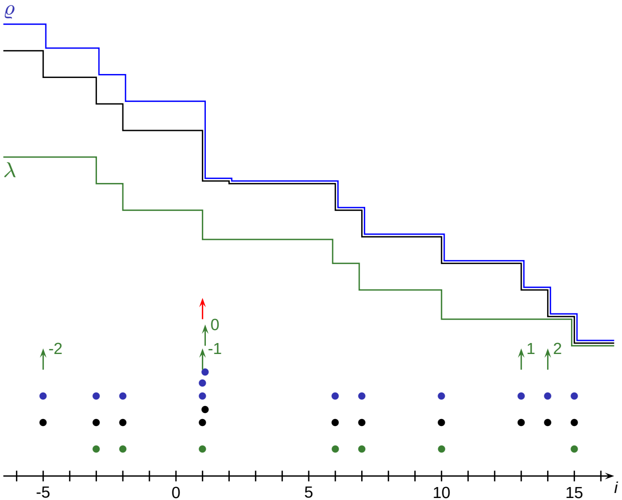

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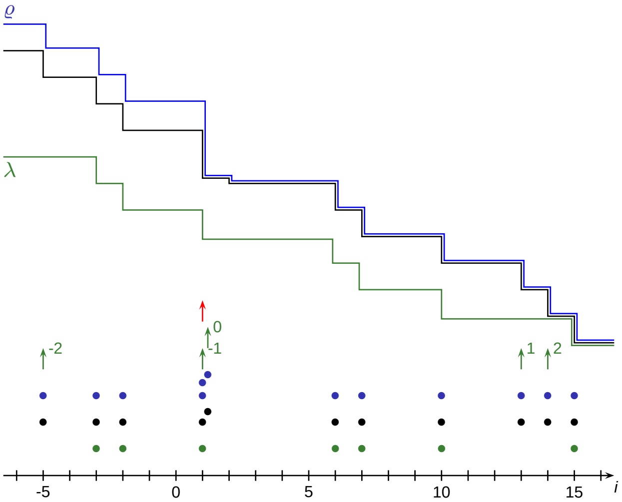

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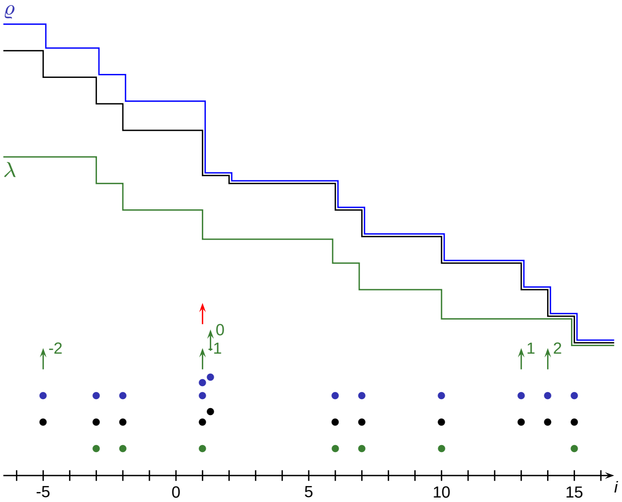

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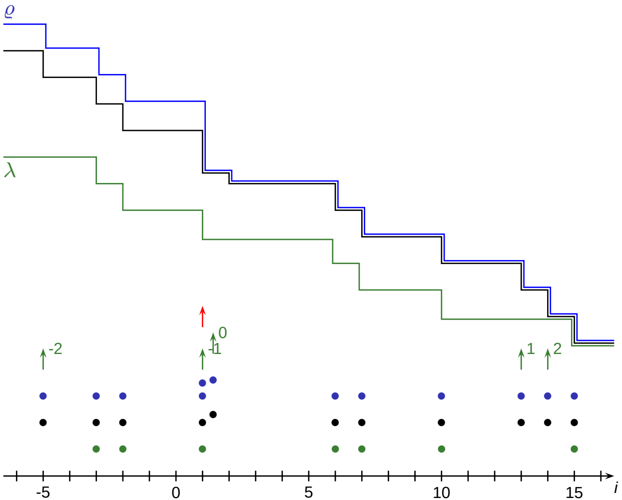

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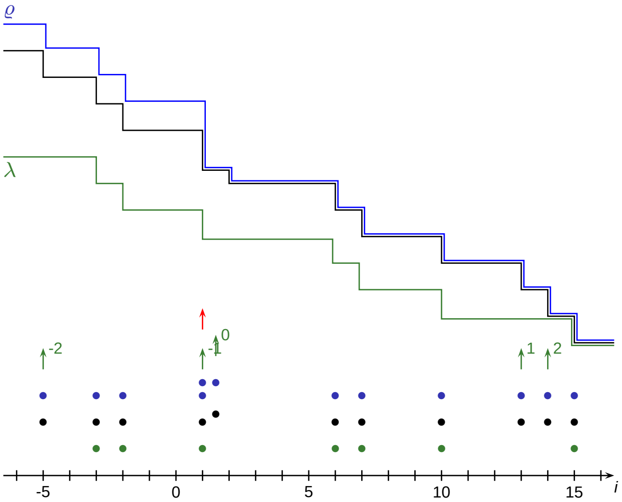

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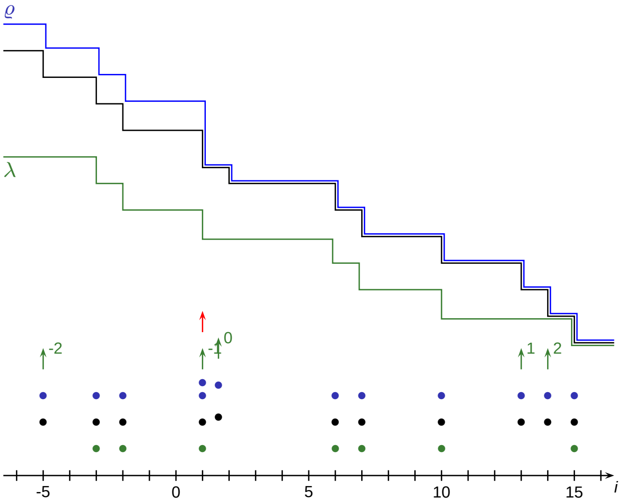

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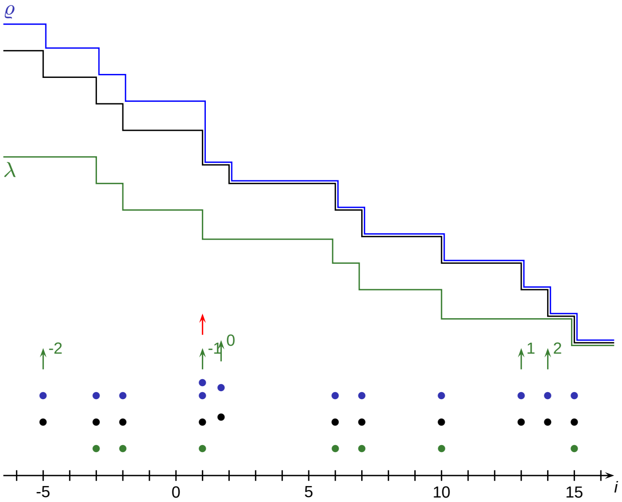

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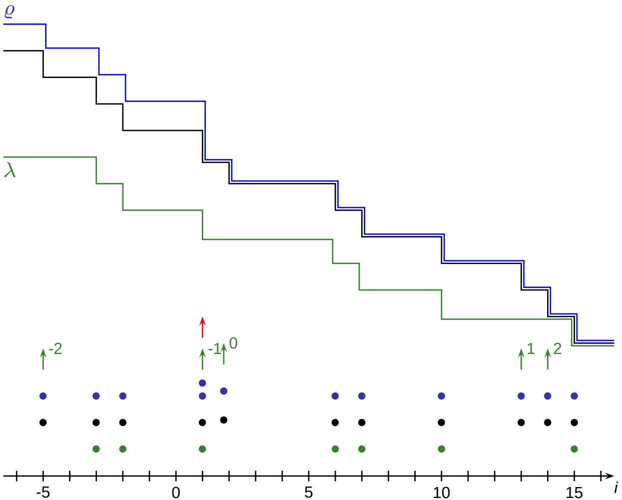

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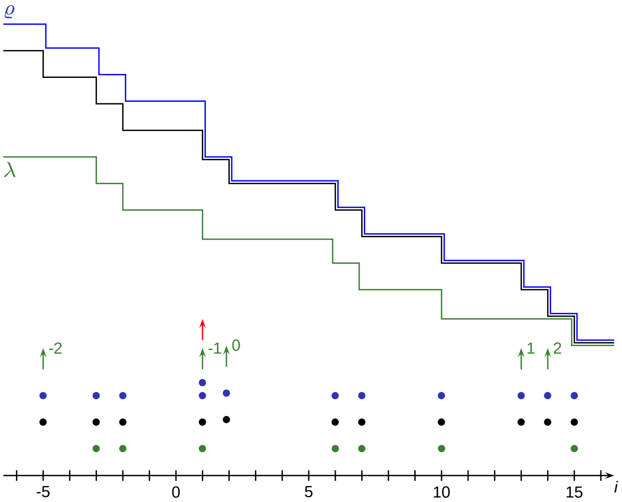

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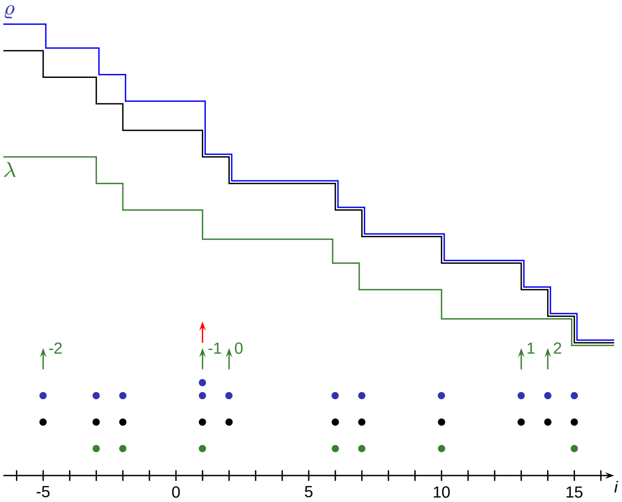

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We say that a model has the microscopic convexity property, if there is such a three-process coupling by which $Q(t) \geq X(t) -$tight error can be achieved.

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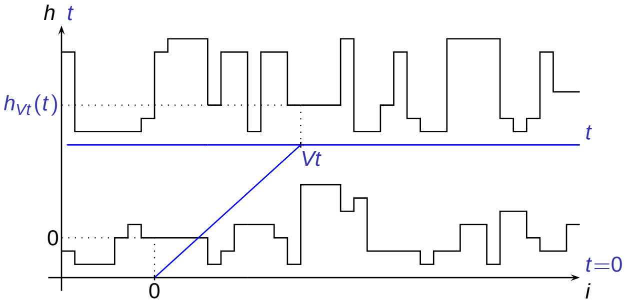

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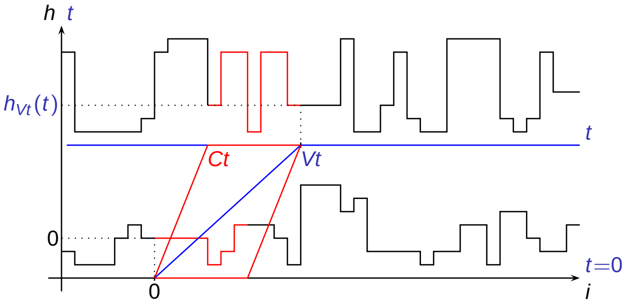

Initial fluctuations are transported along the characteristics on this scale.

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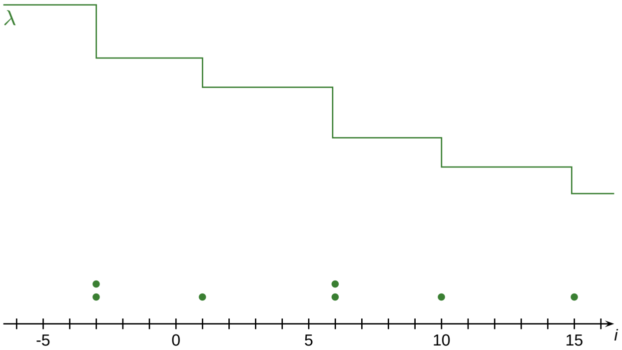
There are limit distribution results for TASEP e.g. by Johansson 2000, Prähofer and Spohn 2001, Ferrari and Spohn 2006.
Their methods give limit distributions as well, but are very model-dependent: they rewrite the model as a determinantal process, and perform asymptotic analysis of the determinants.

Proof: many second class particles



Second class particle current: difference in growth.

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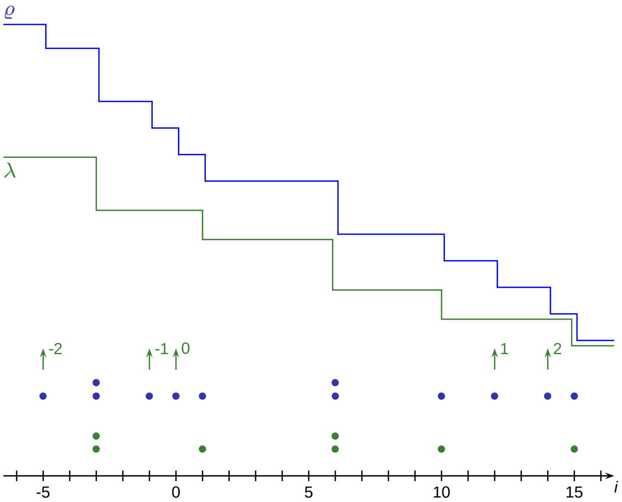

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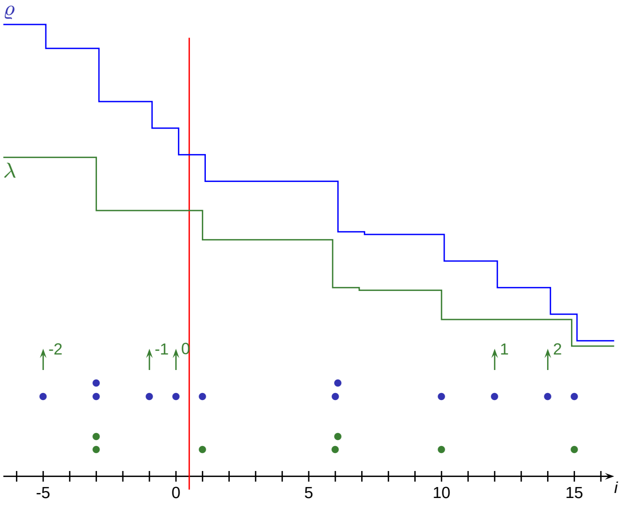

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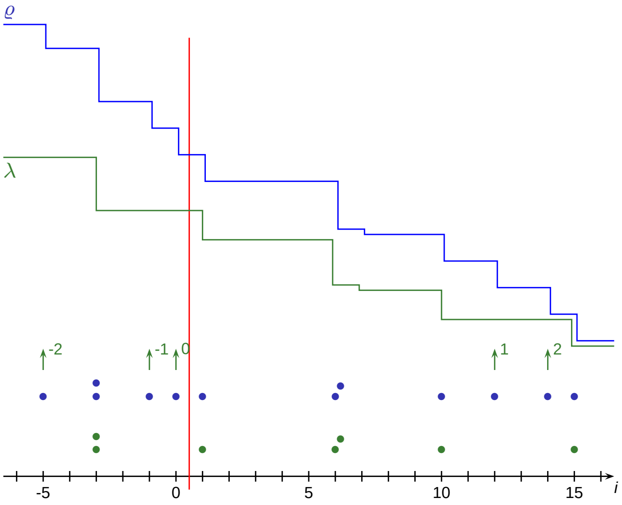

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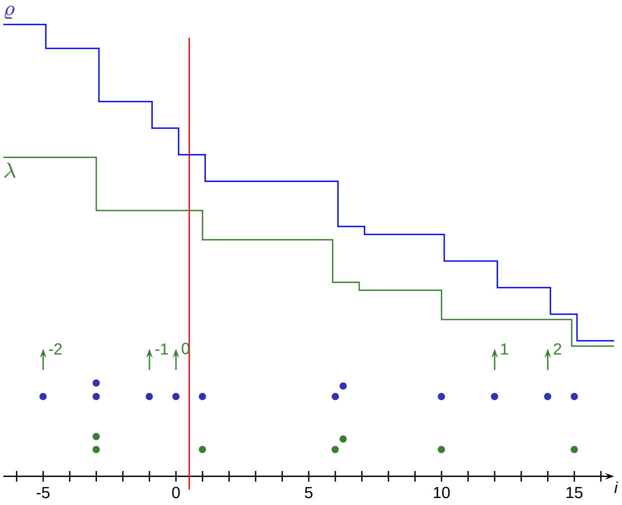

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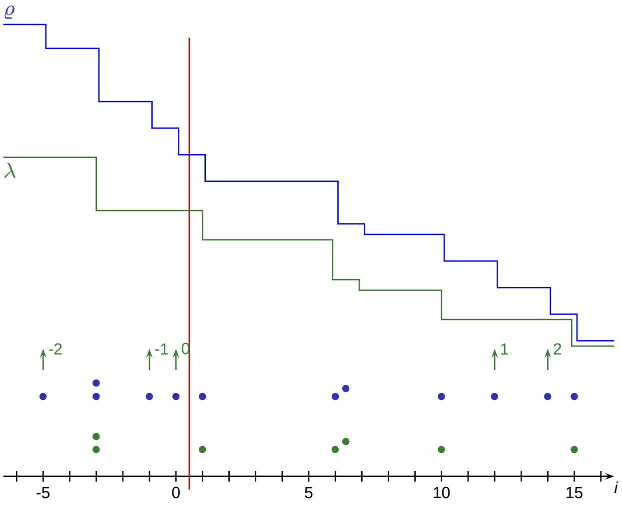

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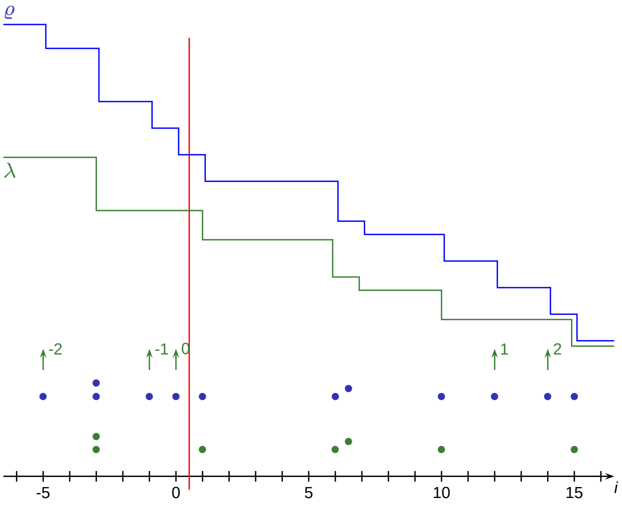

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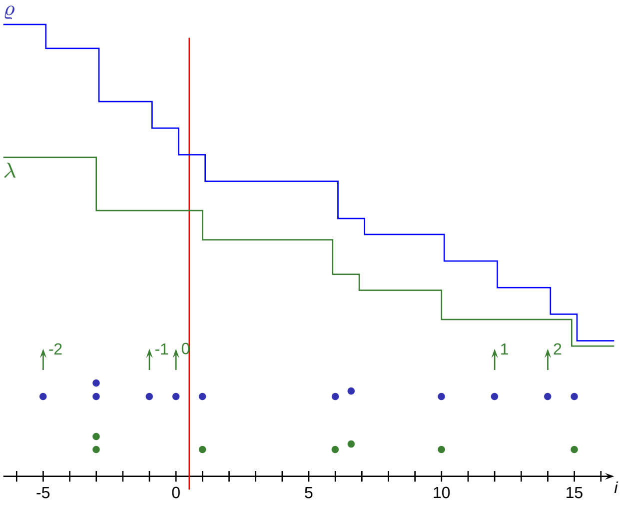

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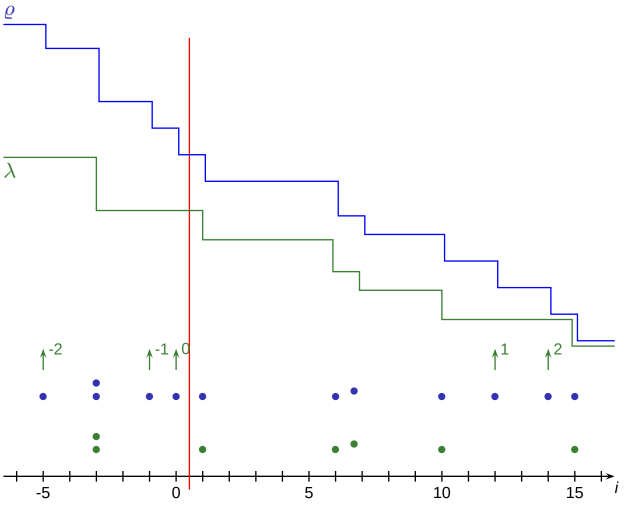

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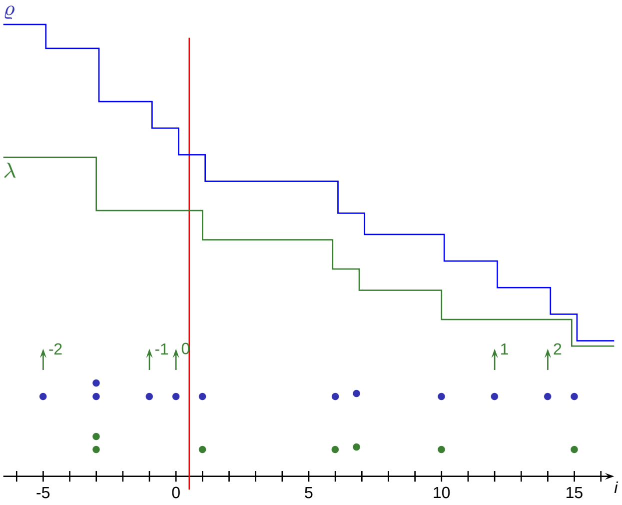

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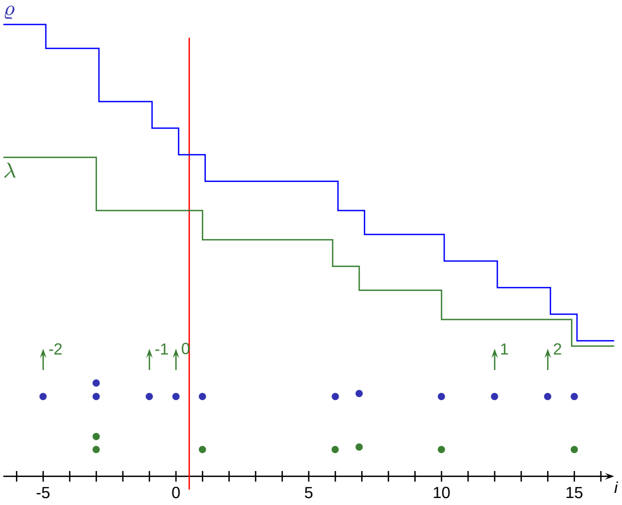

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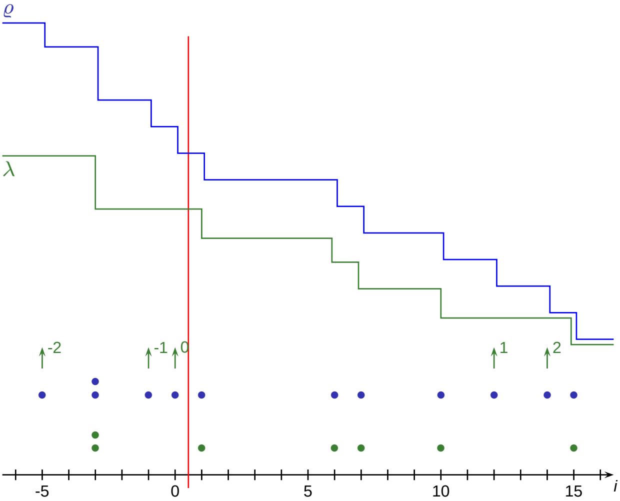

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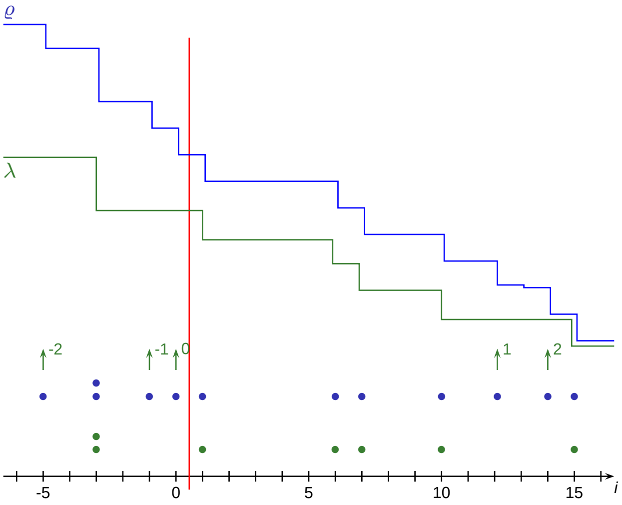

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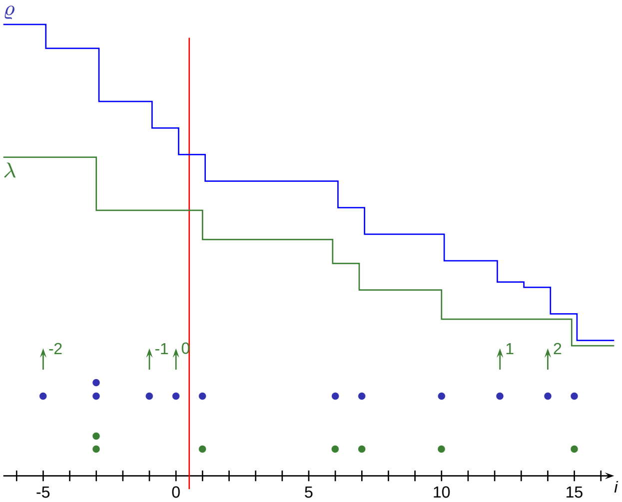

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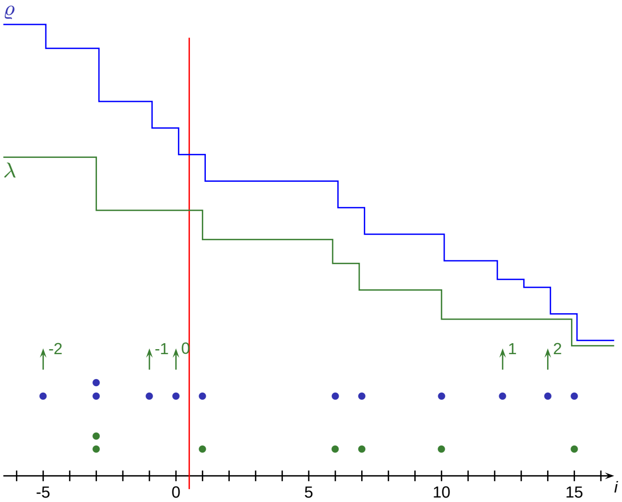

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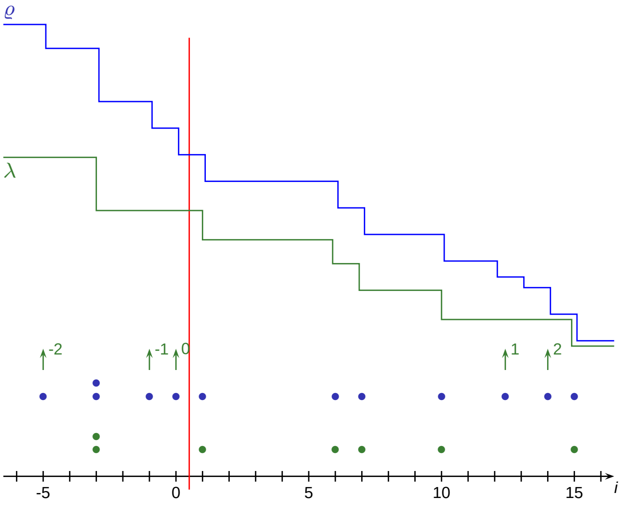

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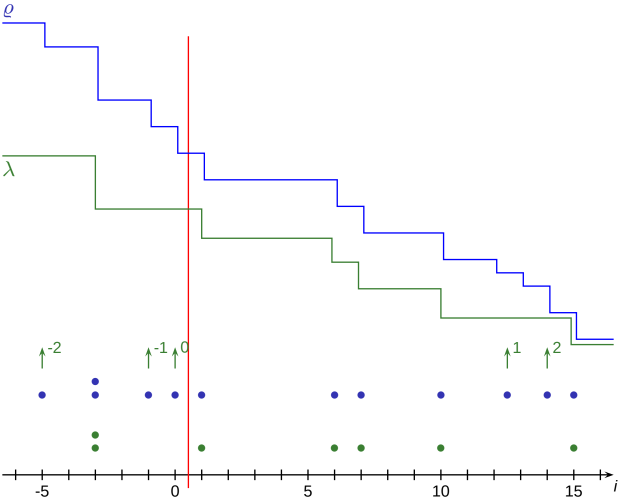

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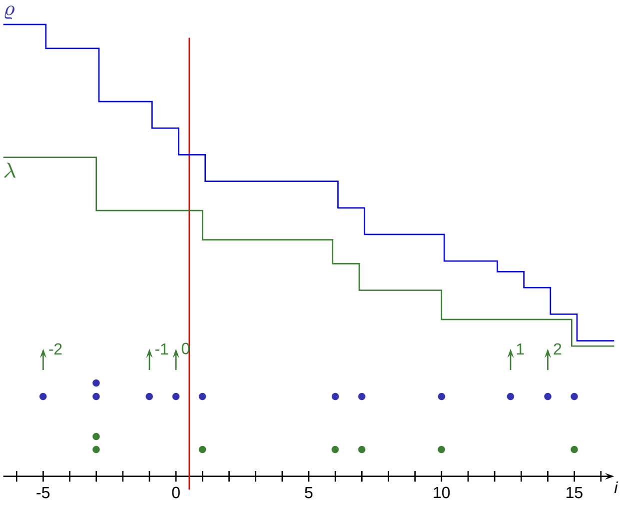

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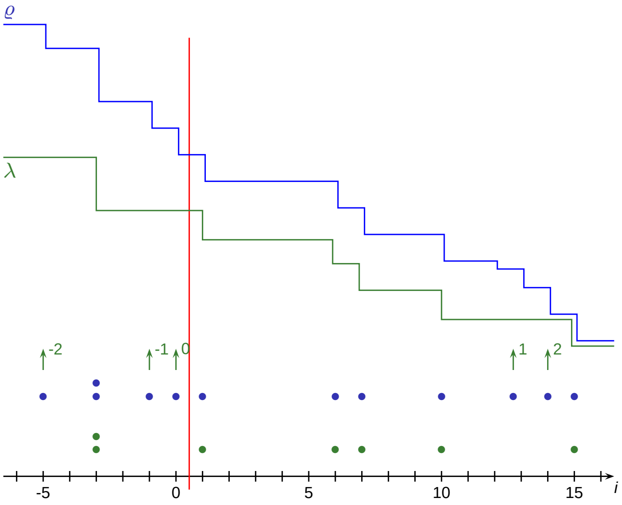

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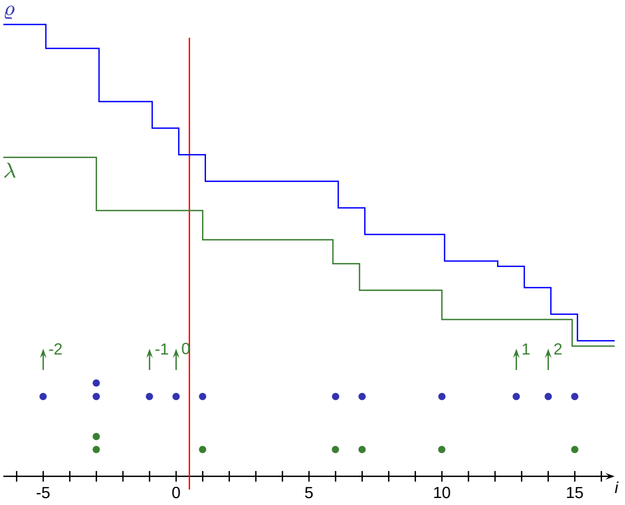

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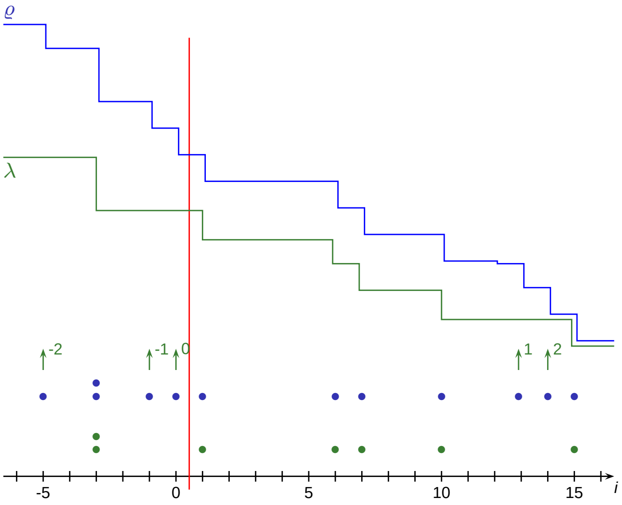

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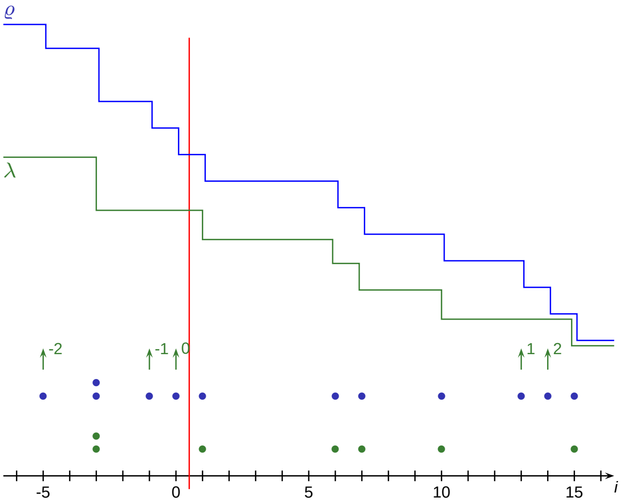

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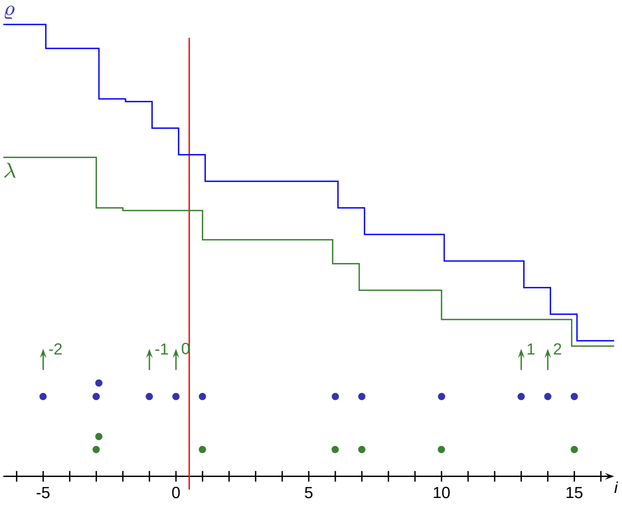

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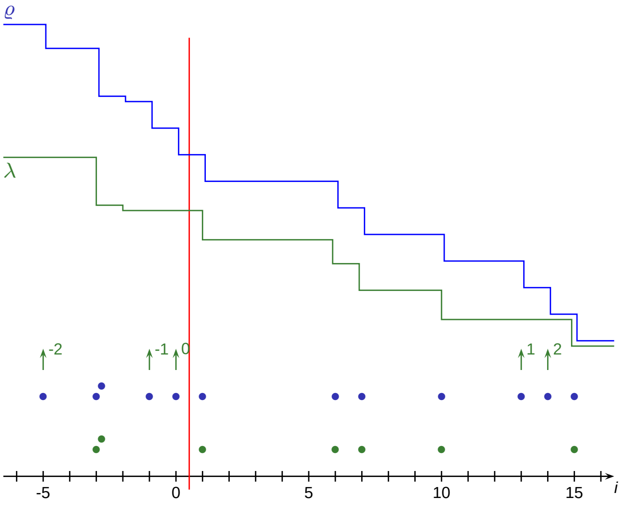

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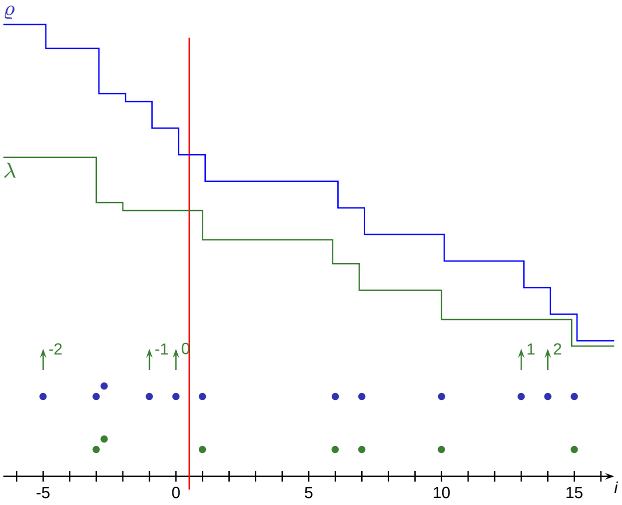

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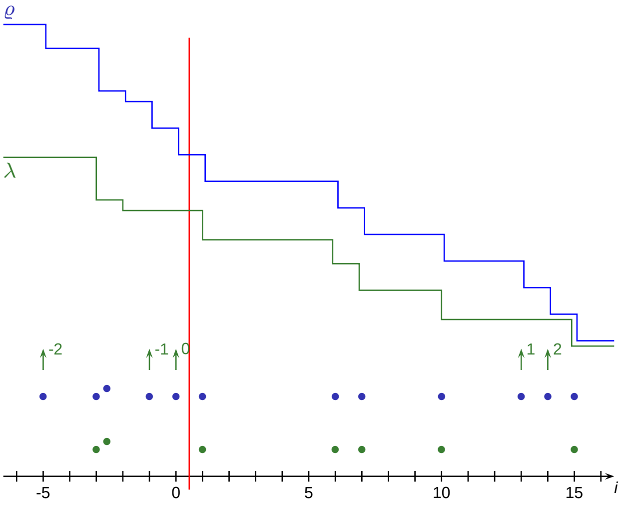

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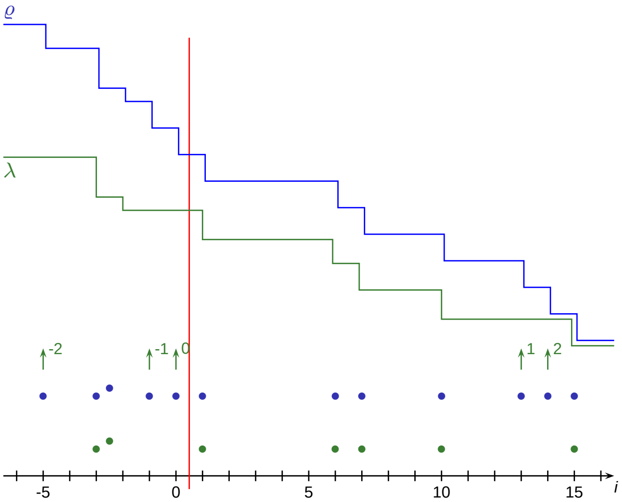

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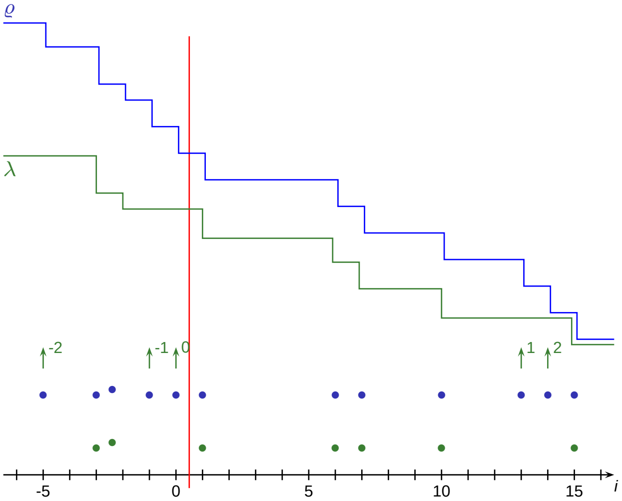

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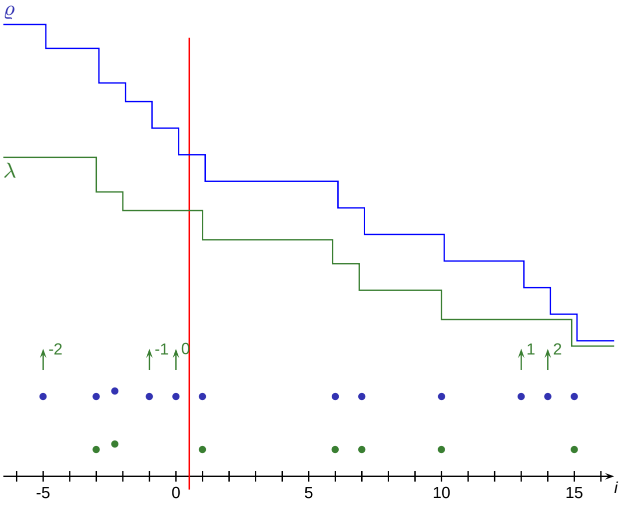

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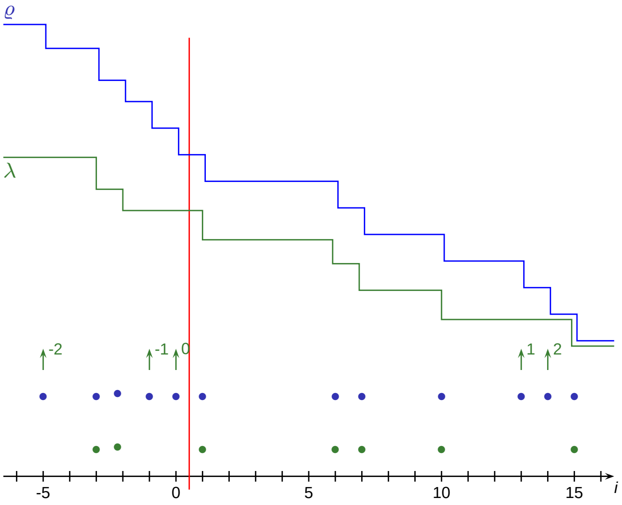

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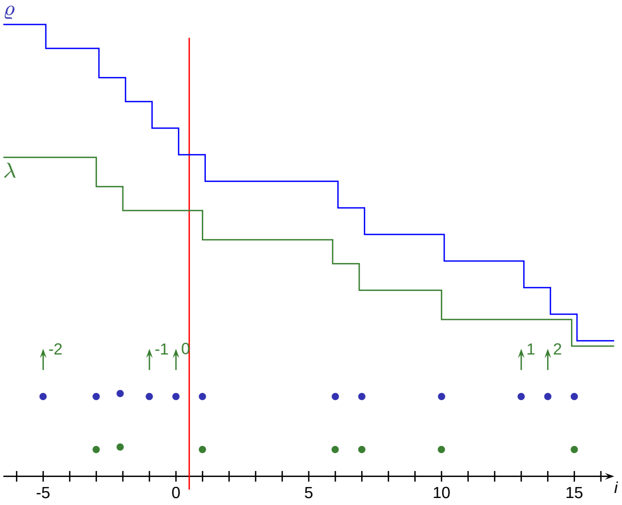

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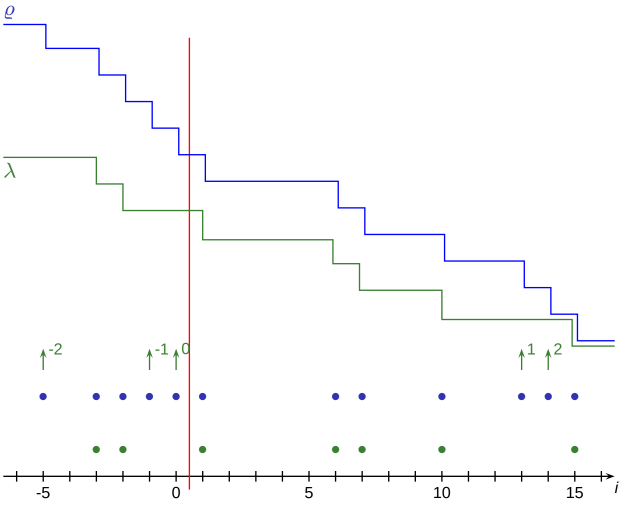

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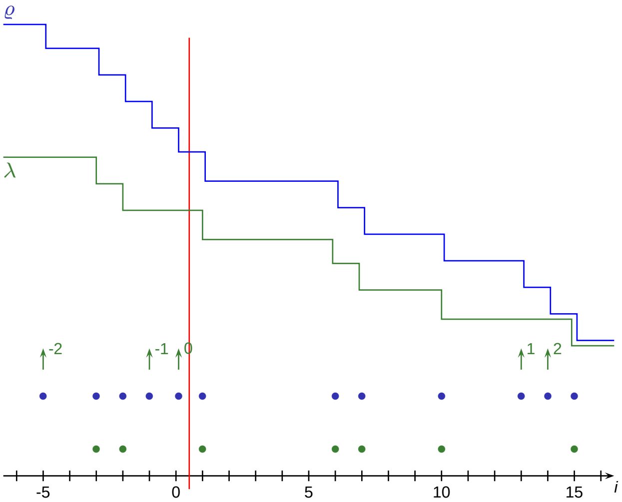

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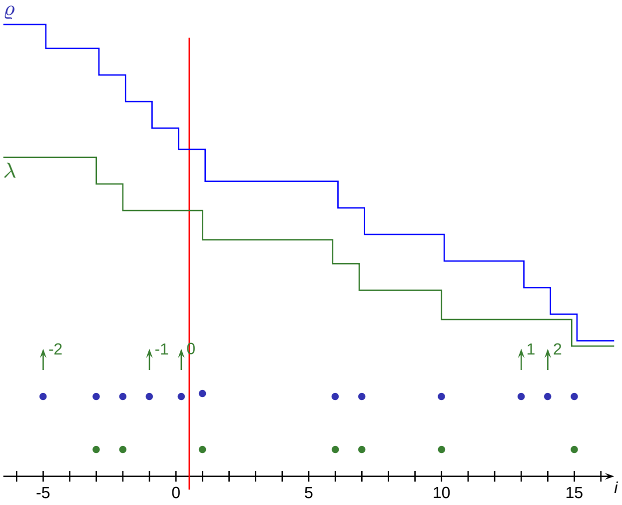

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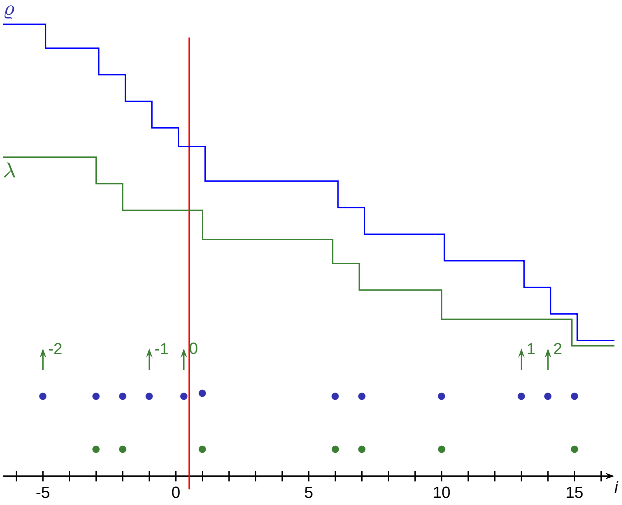

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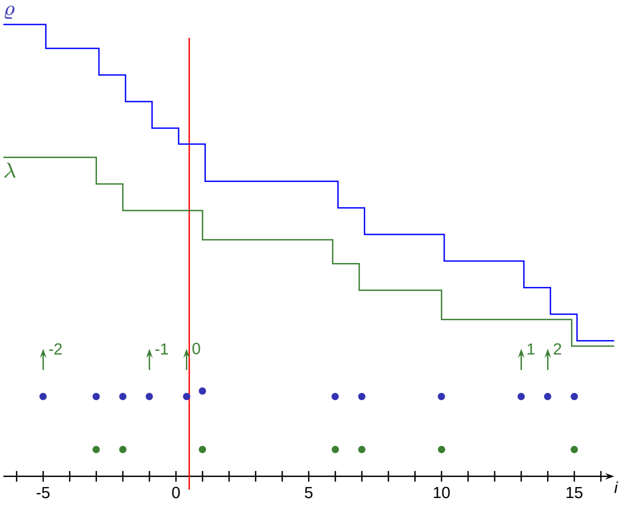

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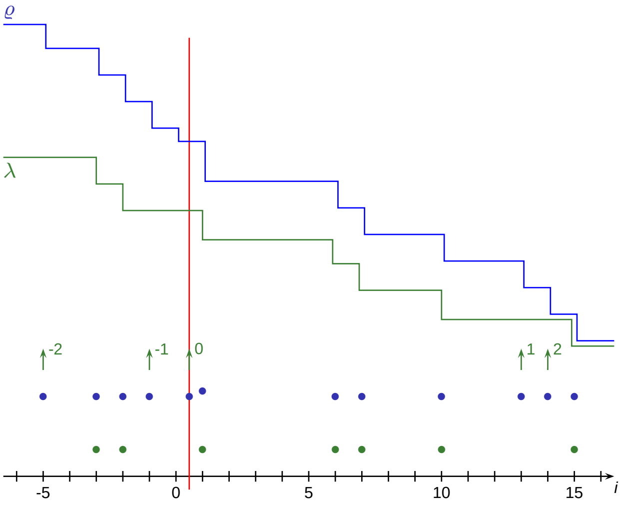

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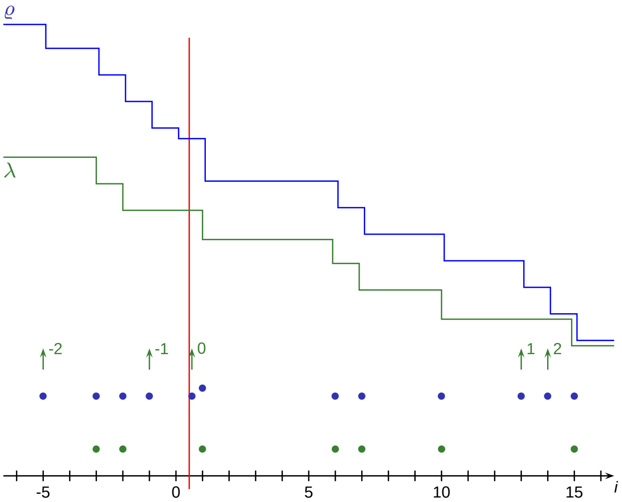

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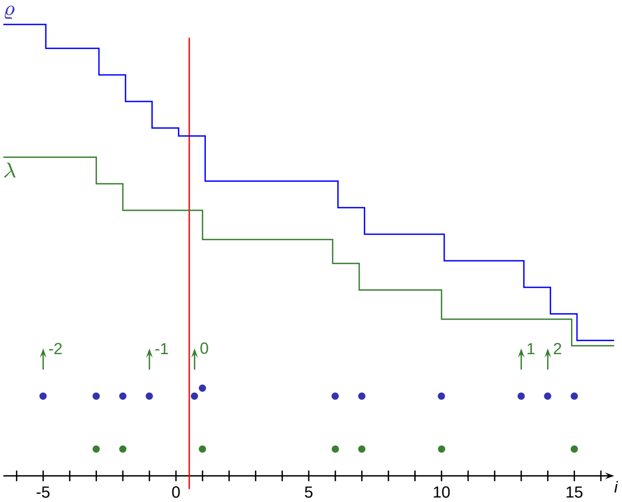

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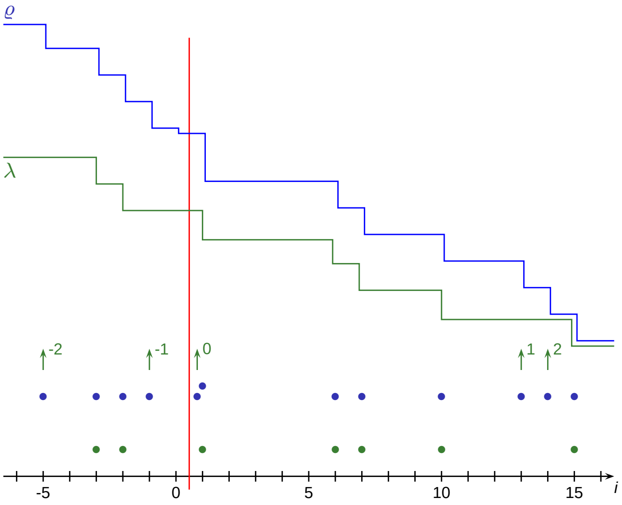

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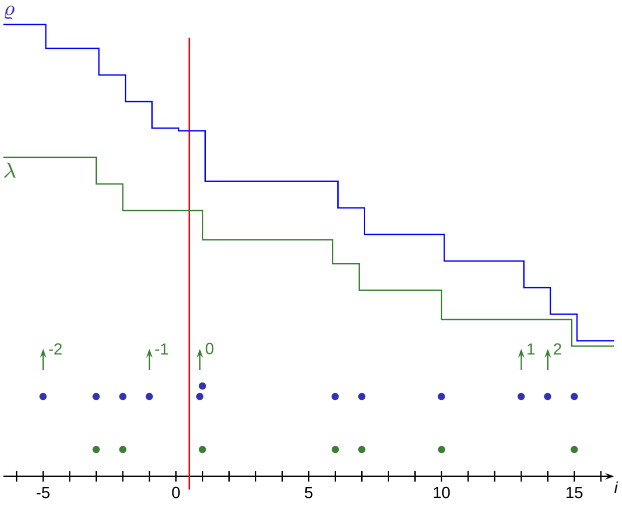

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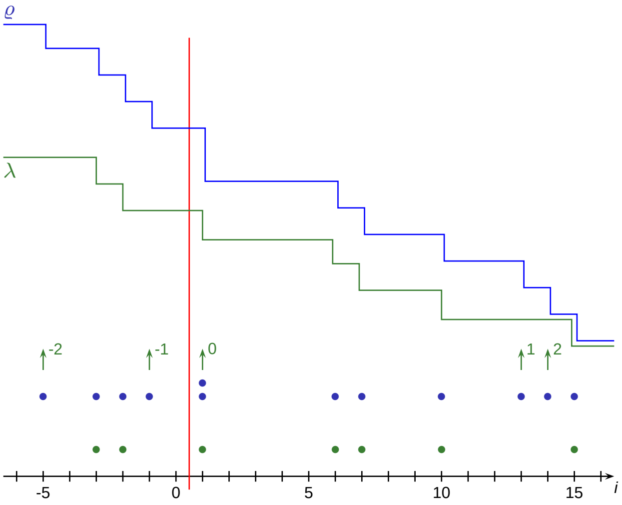

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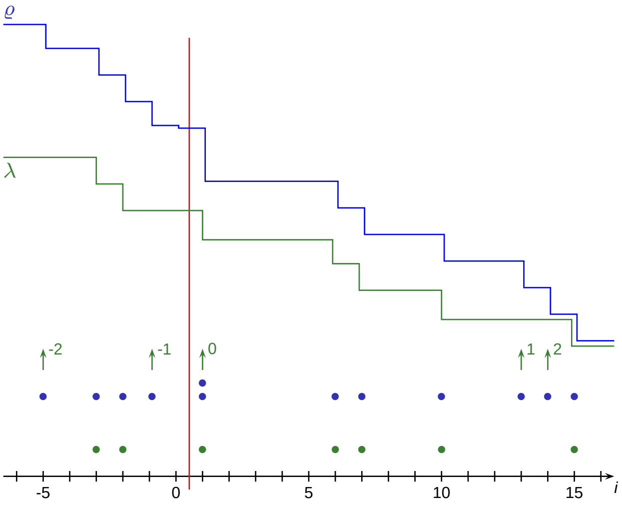

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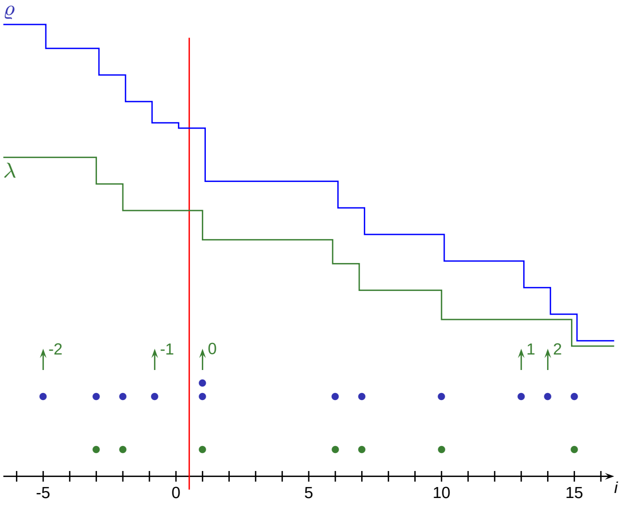

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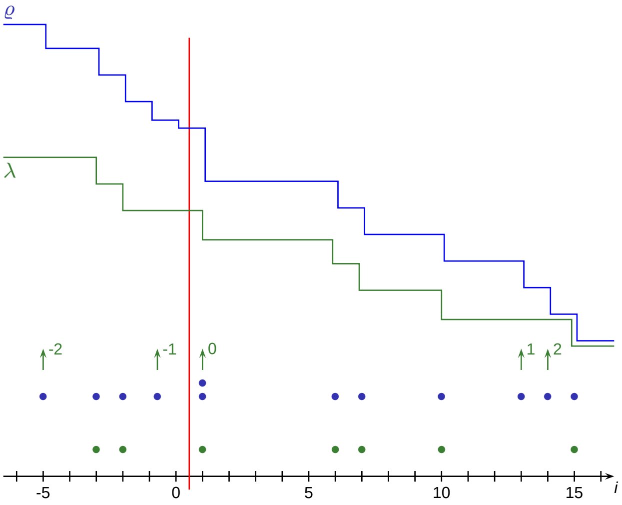

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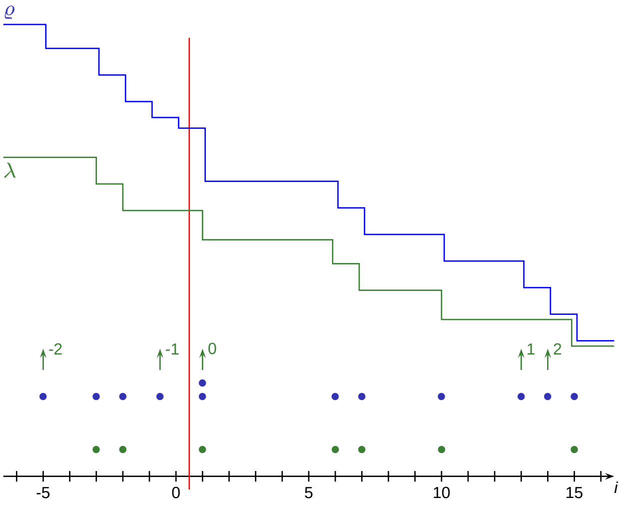

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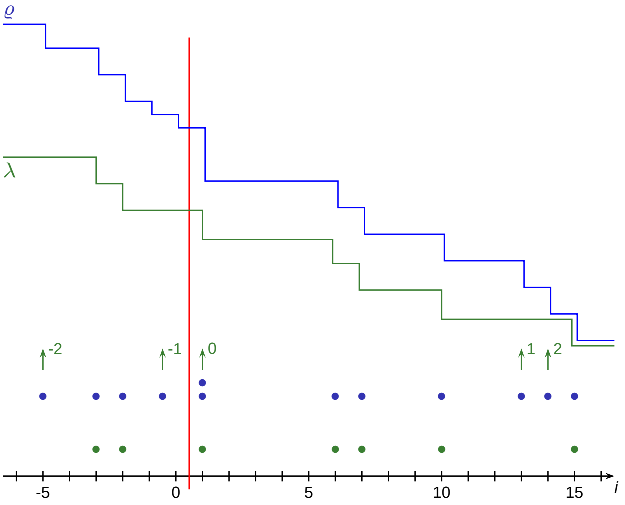

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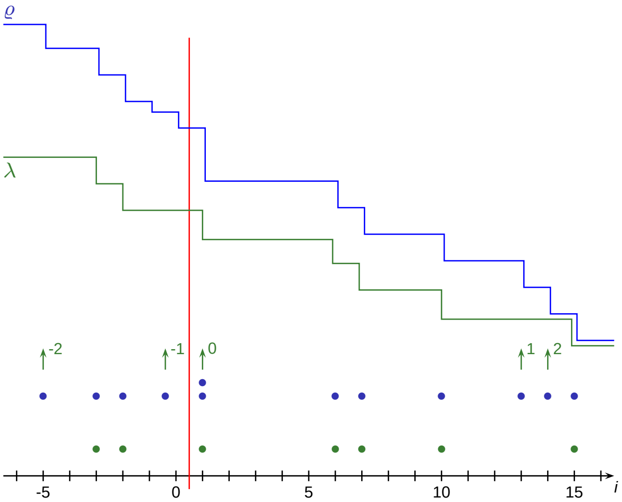

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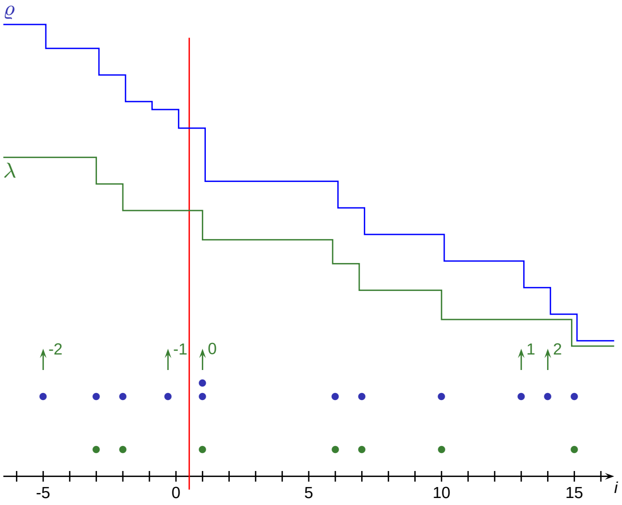

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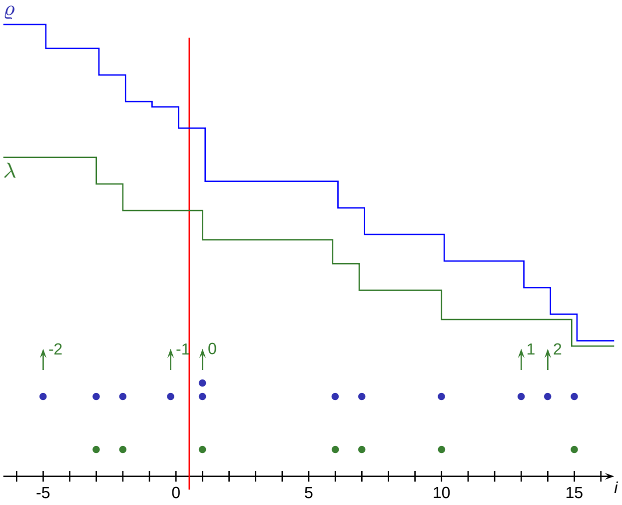

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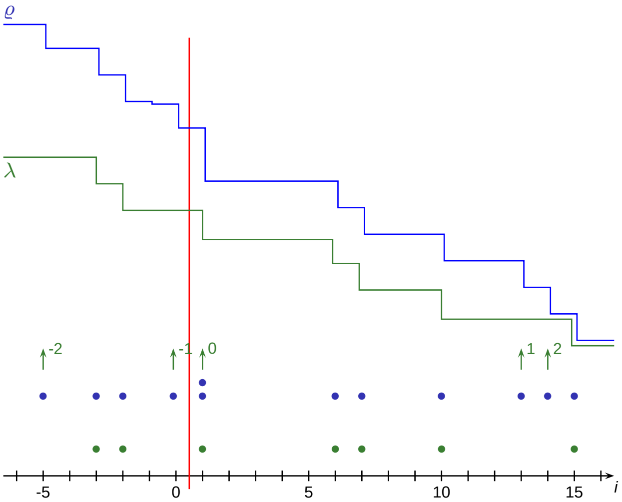

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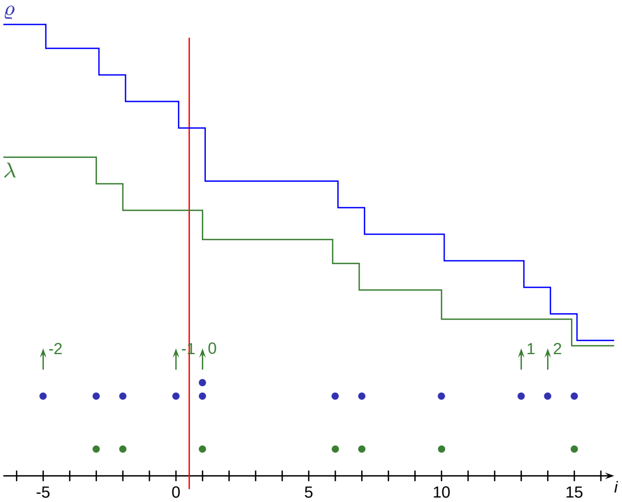

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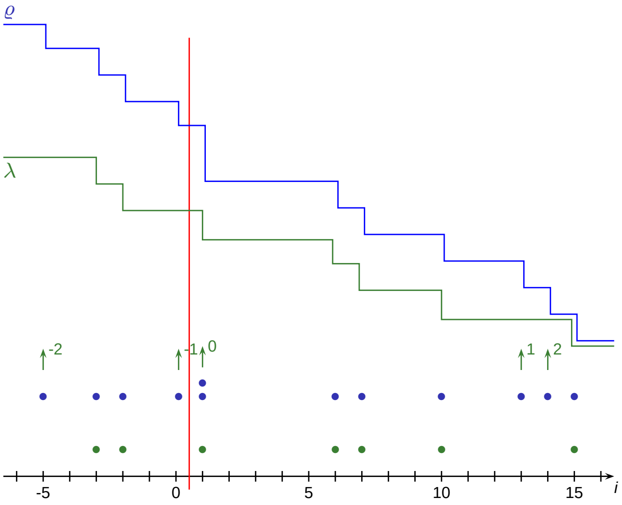

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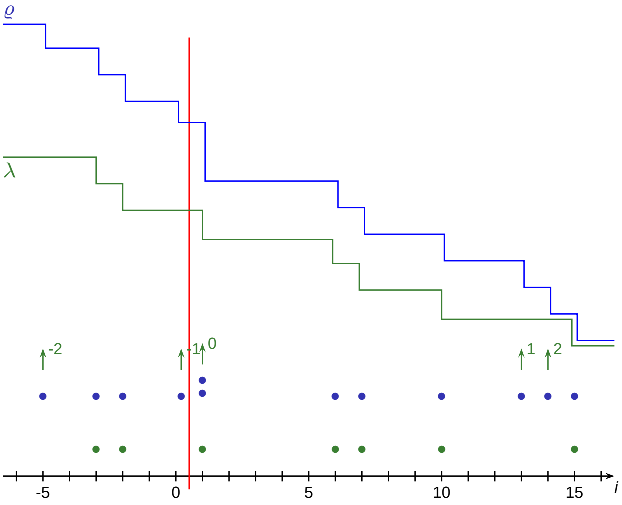

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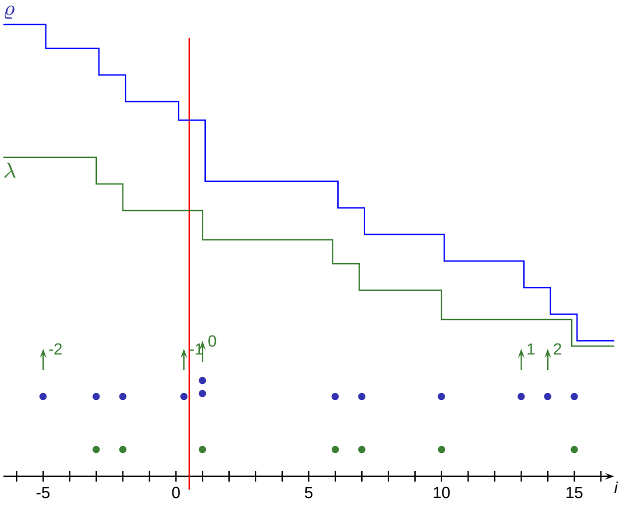

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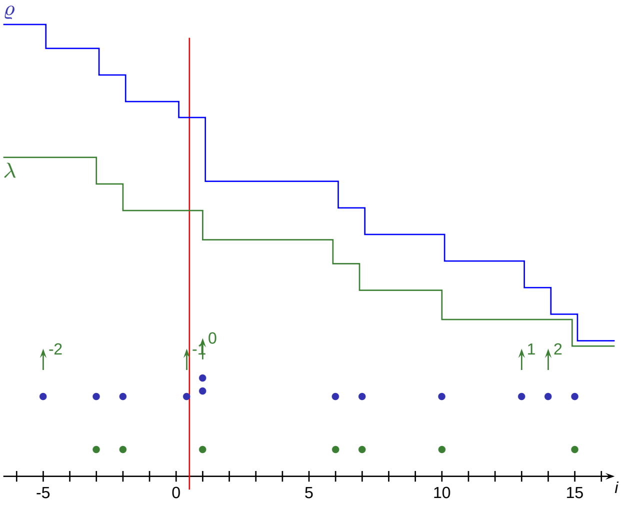

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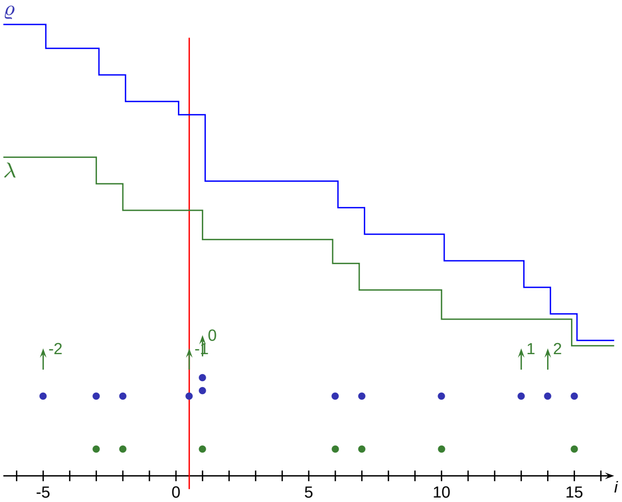

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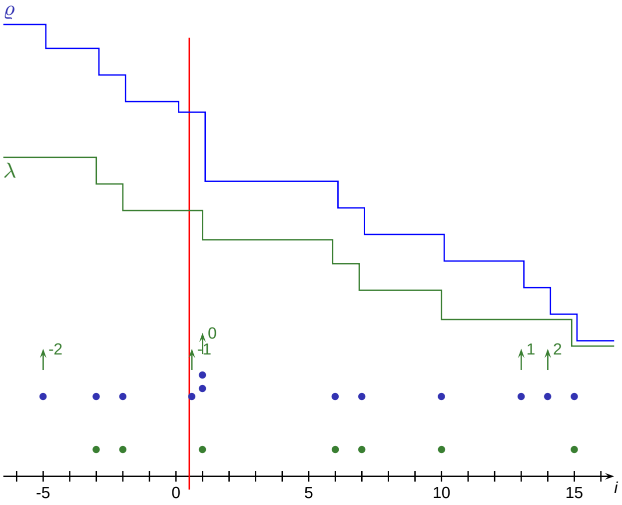

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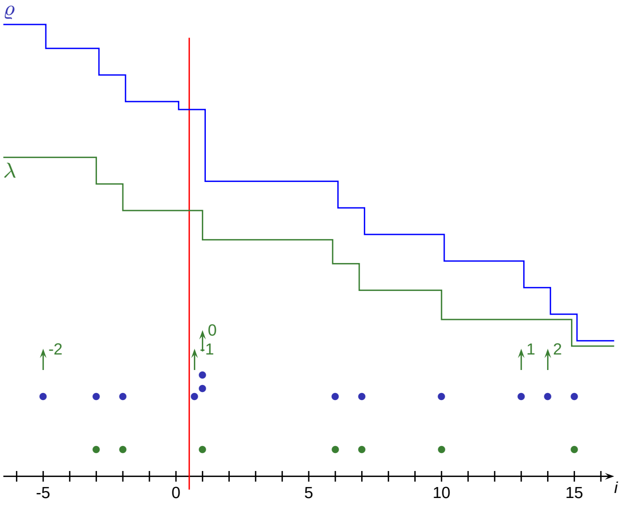

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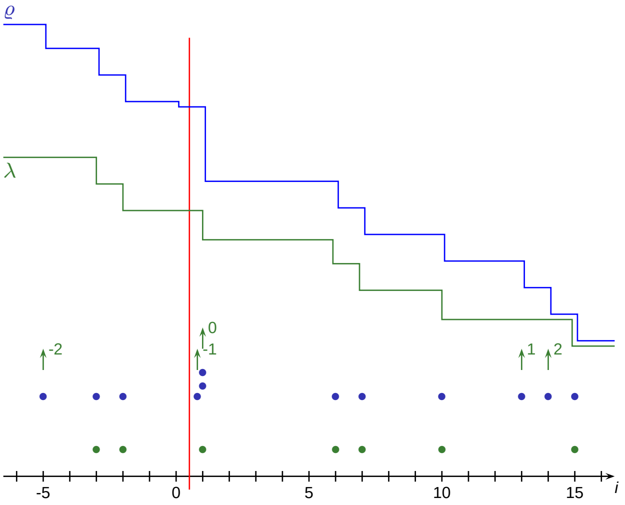

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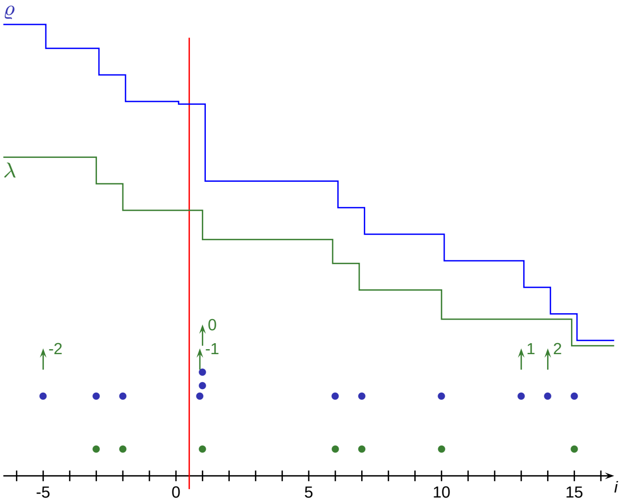

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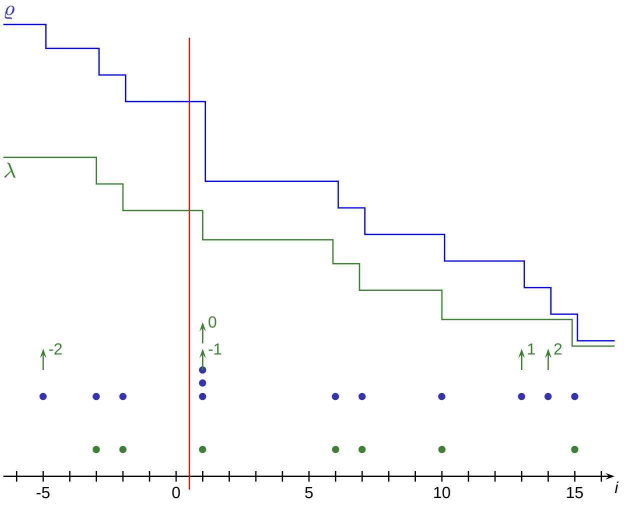

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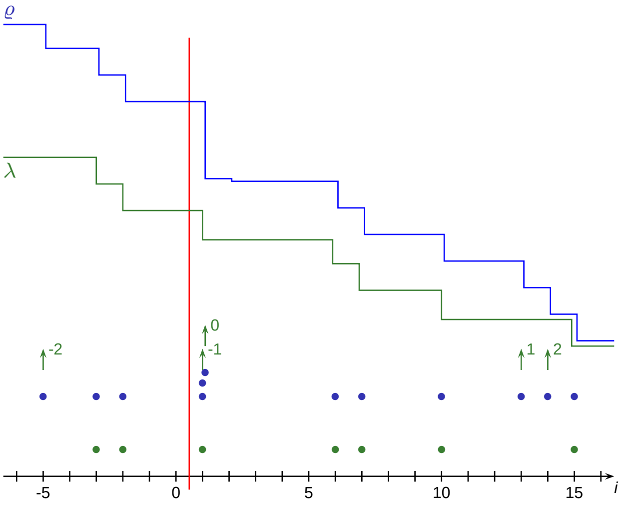

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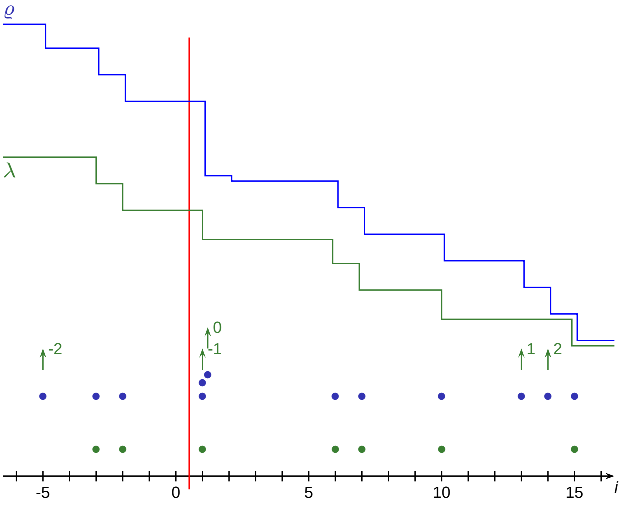

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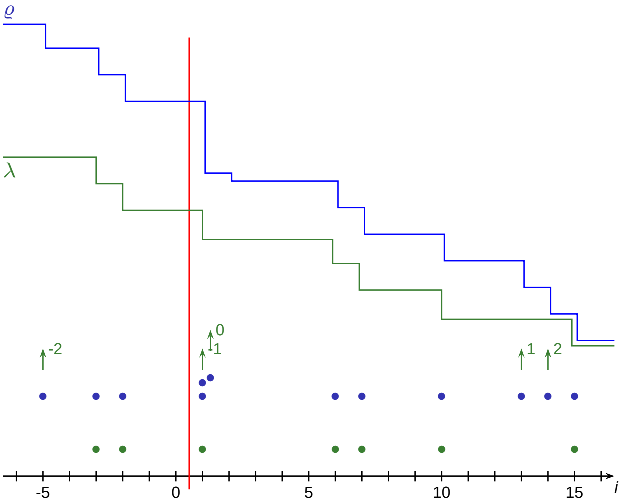

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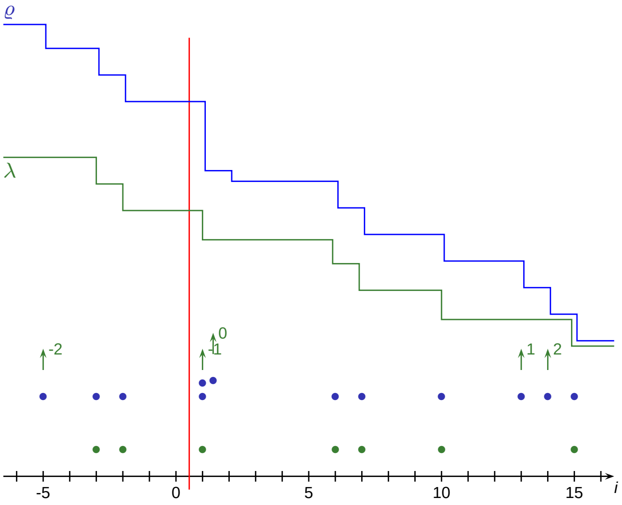

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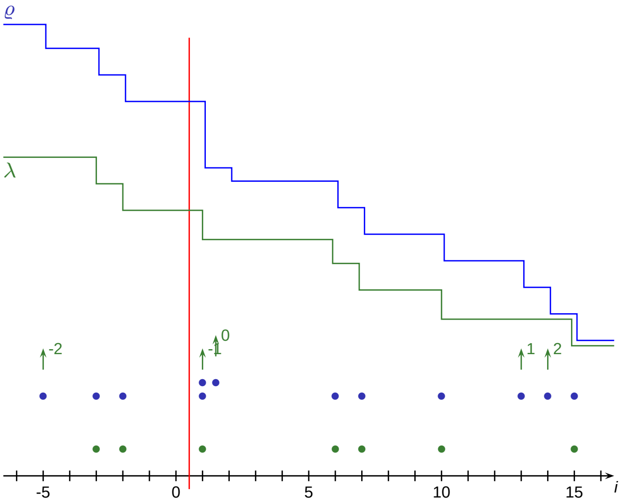

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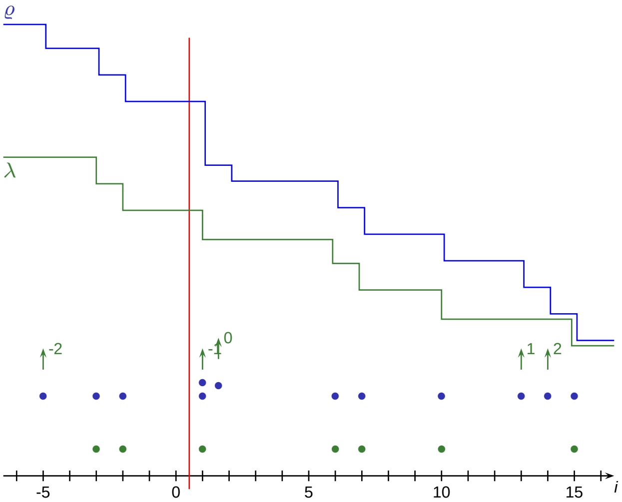

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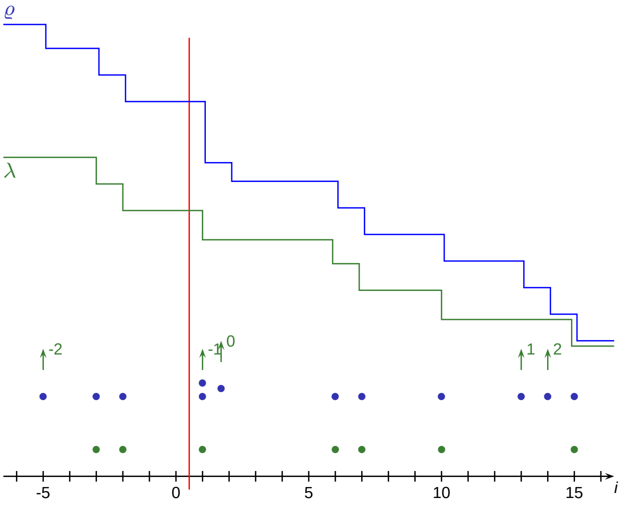

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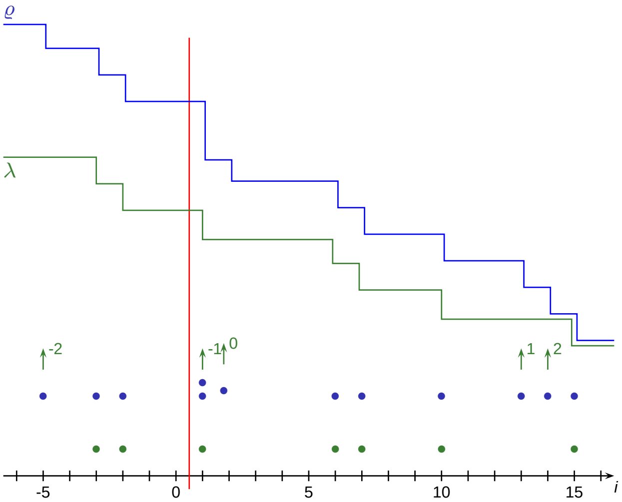

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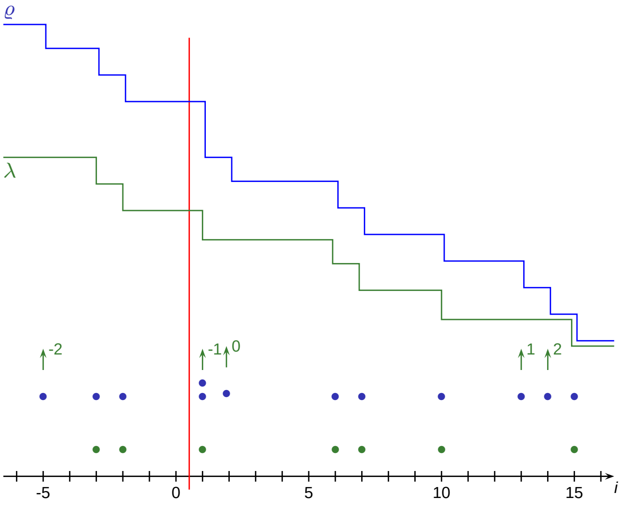

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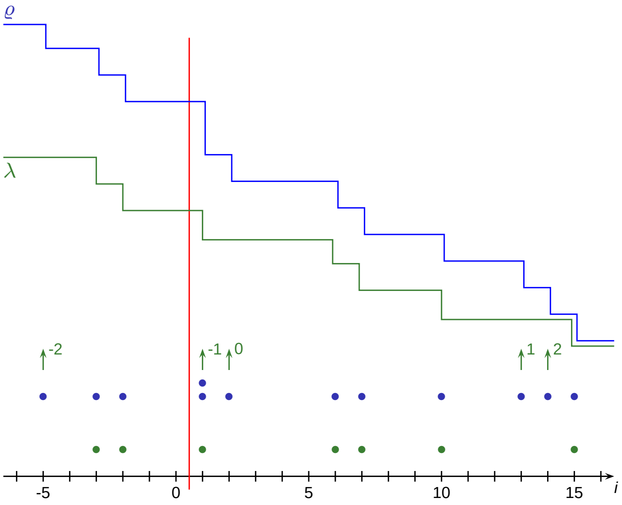

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The computations result in (remember $\mathbf{E}(Q(t)) = Ct$)

$$\mathbf{P}\{Q(t) - Ct \ge u\} \le c \cdot \frac{t^2}{u^4} \cdot \mathbf{Var}(h_{Ct}(t)).$$

Upper bound

Theorem (B. - Seppäläinen; also ideas from B. Tóth, H. Spohn and M. Prähofer**)**

Started from (almost) equilibrium,

$$\mathbf{Var}(h_{Ct}(t)) = c \cdot \mathbf{E}|Q(t) - C \cdot t|$$

in the whole family of processes.

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Hence proceed with

$$\mathbf{P}\{Q(t) - Ct \geq u\} \leq c \cdot \frac{t^2}{u^4} \cdot \mathbf{Var}(h_{Ct}(t))$$
$$= c \cdot \frac{t^2}{u^4} \cdot \mathbf{E}|Q(t) - C \cdot t|.$$

Upper bound

With

$$\widetilde{Q}(t) := Q(t) - Ct \qquad \text{and} \qquad E := \mathbf{E}|\widetilde{Q}(t)|,$$

we have (with a similar lower deviation bound)

$$\mathbf{P}\{|\widetilde{Q}(t)| > u\} \le c \cdot \frac{t^2}{u^4} \cdot E.$$

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Claim: this already implies the $t^{2/3}$ upper bound:

Upper bound

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$$= E \int_0^\infty \mathbf{P}\{|\widetilde{Q}(t)| > vE\} \,\mathrm{d}v$$

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that is, $E^3 \leq c \cdot t^2$.

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E = \mathbf{E}|\widetilde{Q}(t)| &= \int_0^\infty \mathbf{P}\{|\widetilde{Q}(t)| > u\}\,\mathrm{d}u \\
&= E \int_0^\infty \mathbf{P}\{|\widetilde{Q}(t)| > vE\}\,\mathrm{d}v \\
&\le E \int_{1/2}^\infty \mathbf{P}\{|\widetilde{Q}(t)| > vE\}\,\mathrm{d}v + \frac{1}{2}E \\
&\le c \cdot \frac{t^2}{E^2} + \frac{1}{2}E,
\end{aligned}$$

that is, $E^3 \le c \cdot t^2$.

$$\begin{aligned}
\mathbf{Var}(h_{Ct}(t)) &\overset{\text{Thm}}{=} \text{const.} \cdot \mathbf{E}|Q(t) - Ct| \\
&= \text{const.} \cdot E \le c \cdot t^{2/3}. \qquad \blacksquare
\end{aligned}$$

Lower bound

In the upper bound, the relevant orders were

$$u \text{ (deviation of } Q(t)) \sim t^{2/3}, \qquad \varrho - \lambda \sim t^{-1/3}.$$

The lower bound works with similar arguments: compare models of which the densities differ by $t^{-1/3}$, and use connections between $Q(t), X(t)$ and heights.

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The critical feature in both the upper bound and lower bound was microscopic convexity/concavity: $Q(t) \geq X(t)$ (convex) or $Q(t) \leq X(t)$ (concave).

Microscopic convexity/concavity

Model	$H(\varrho)$ is	Micro c.?	$t^{2/3}$ law

Microscopic convexity/concavity

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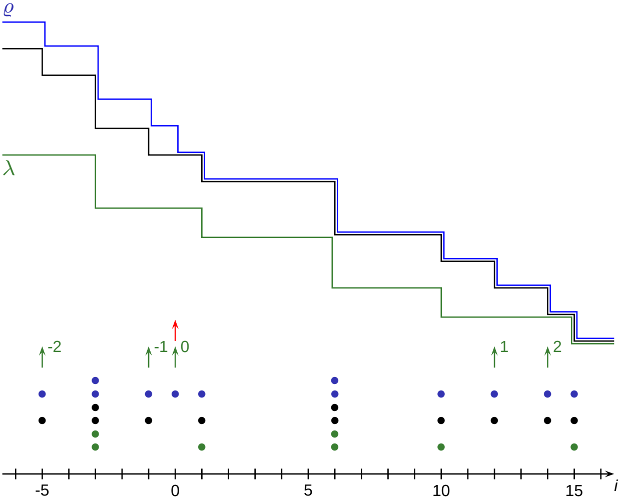
The critical feature: microscopic concavity

$Q(t) \leq X(t) +$ tight error



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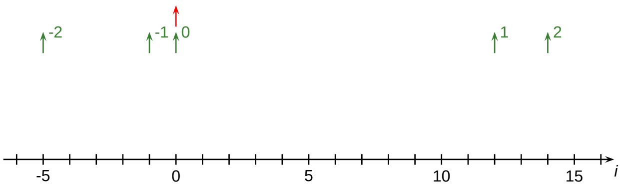

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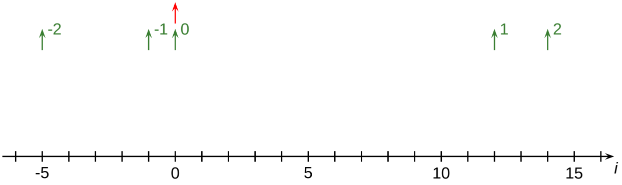

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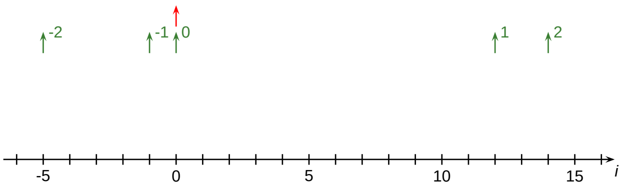

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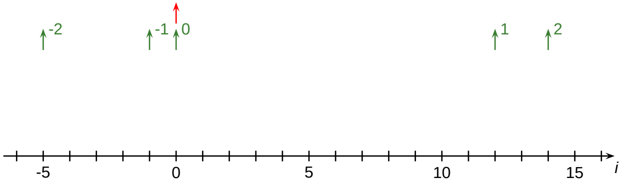

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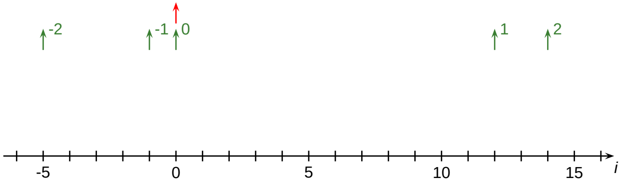

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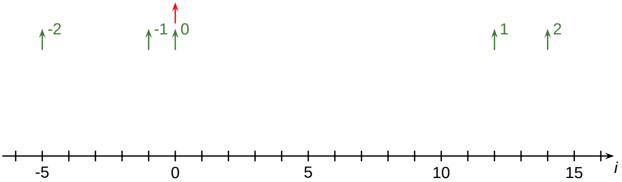

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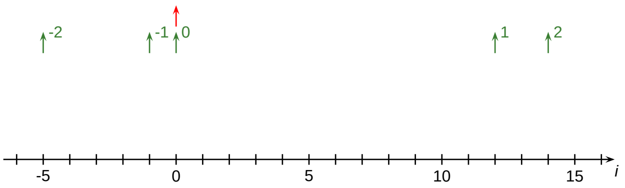

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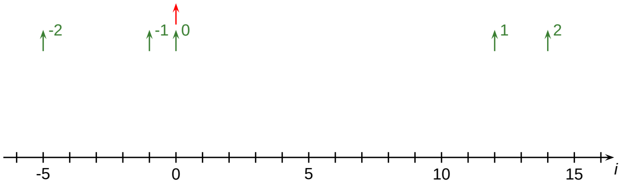

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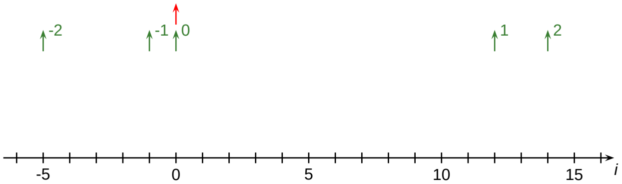

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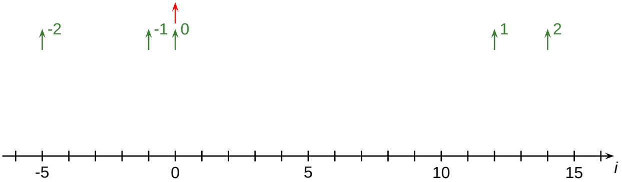

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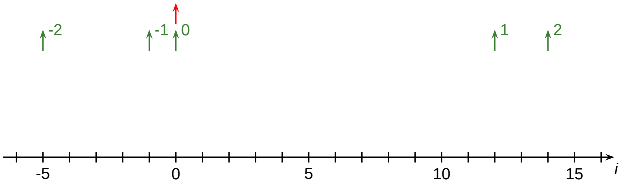

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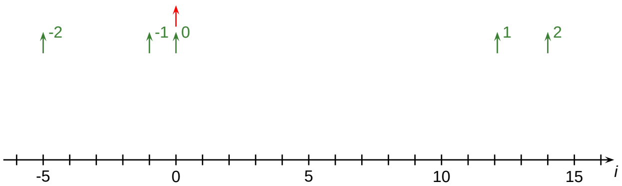

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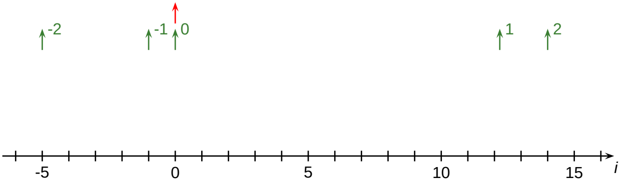

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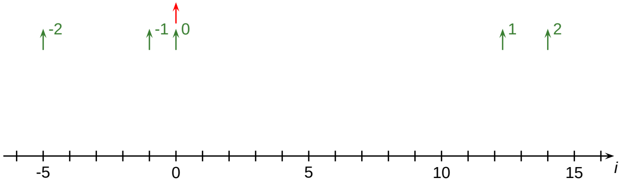

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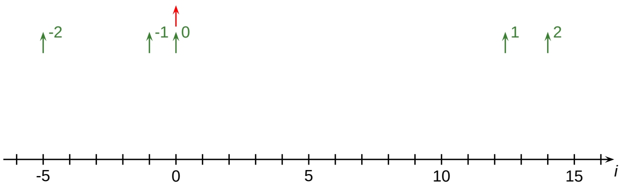

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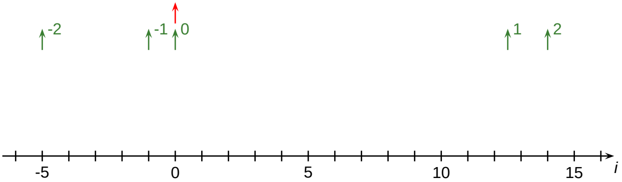

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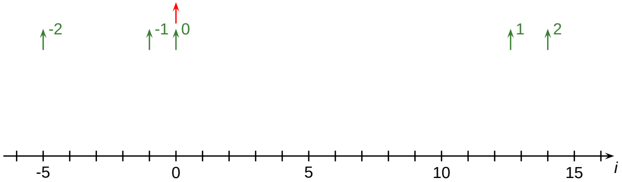

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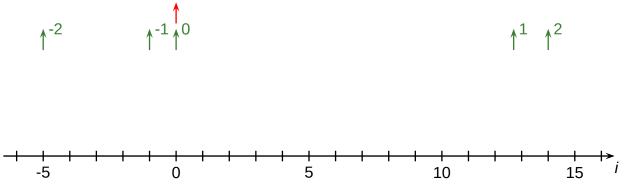

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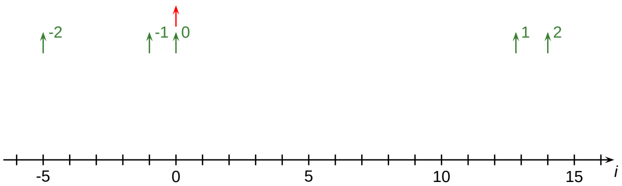

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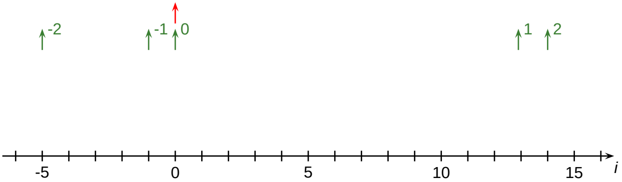

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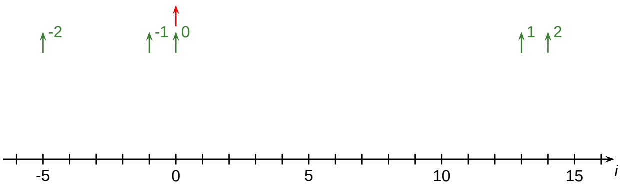

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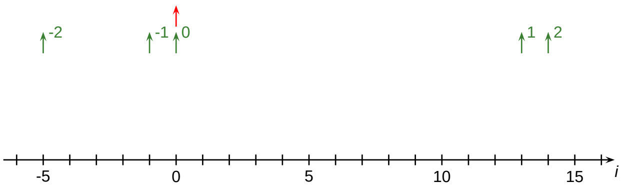

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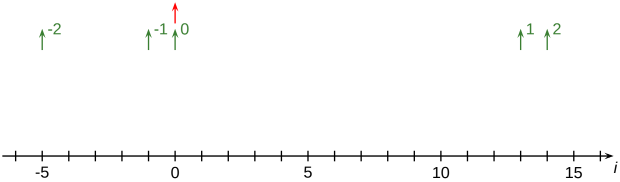

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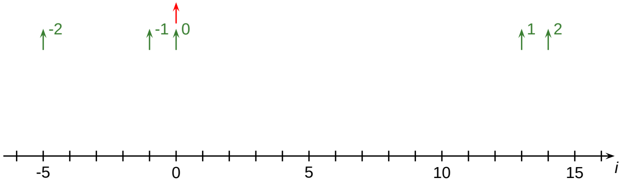

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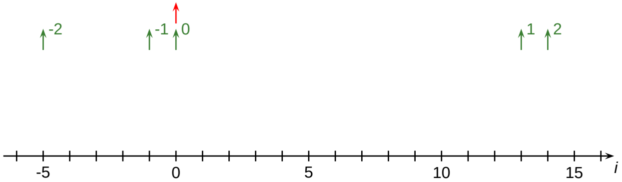

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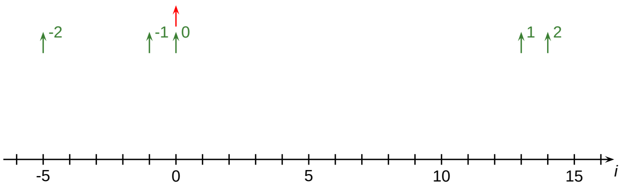

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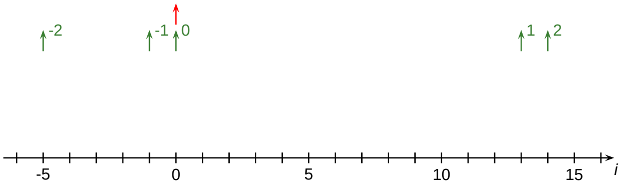

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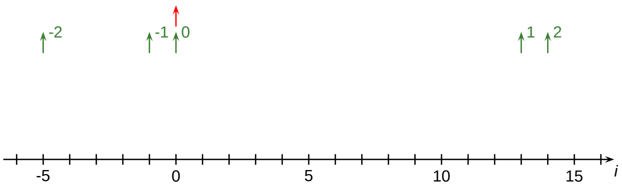

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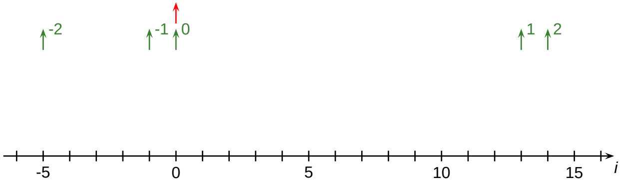

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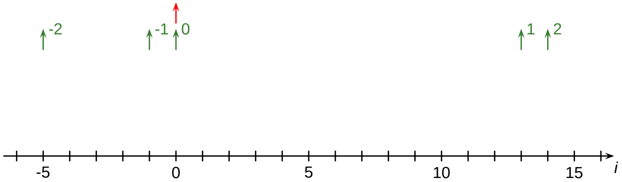

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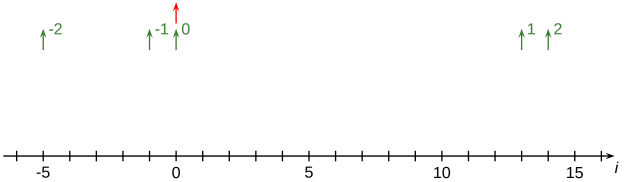

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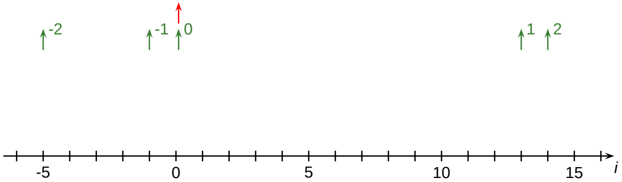

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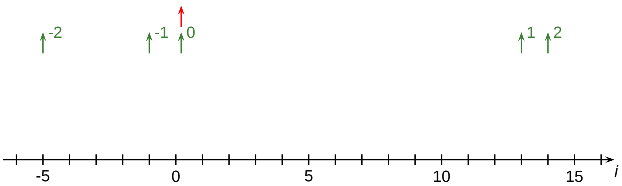

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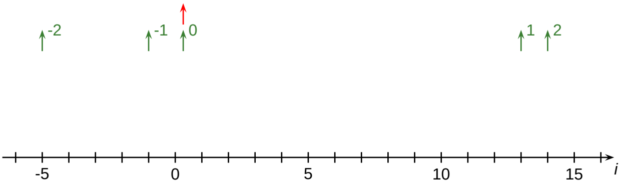

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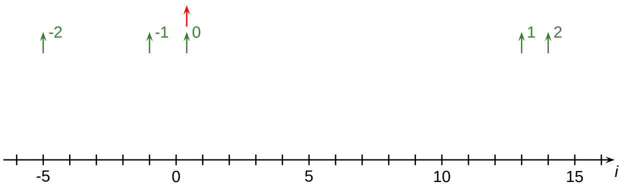

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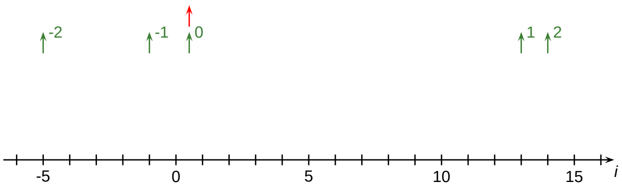

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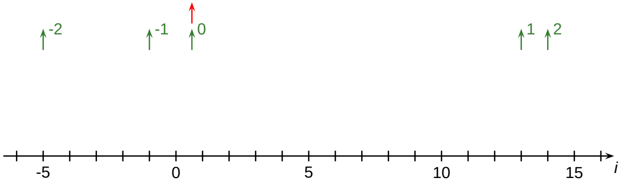

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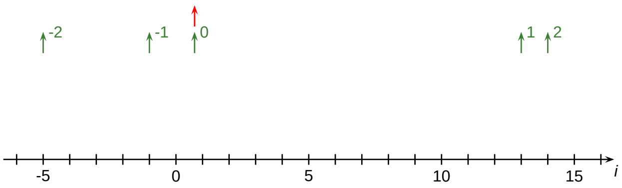

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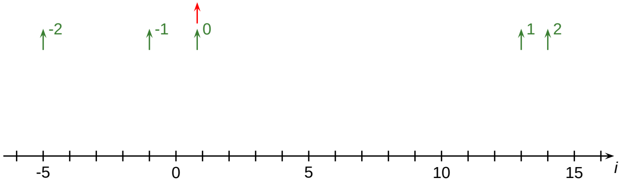

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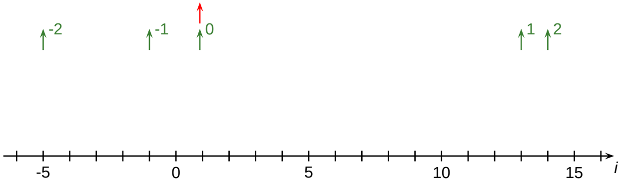

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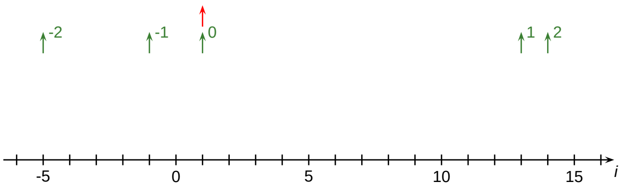

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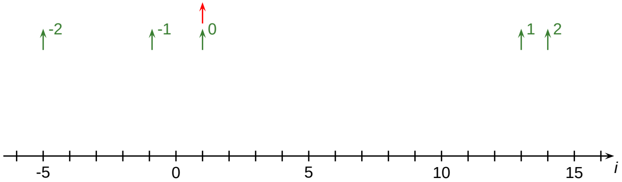

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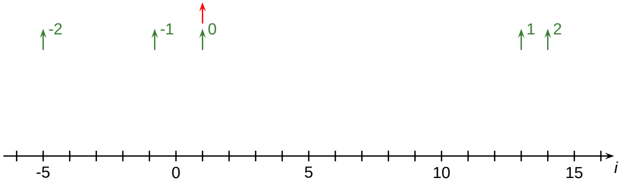

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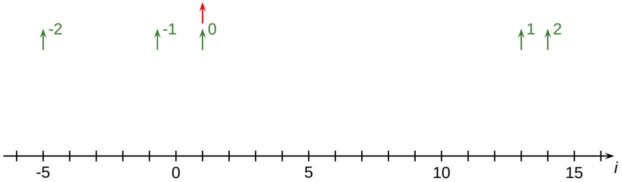

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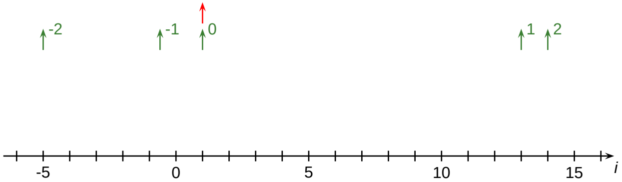

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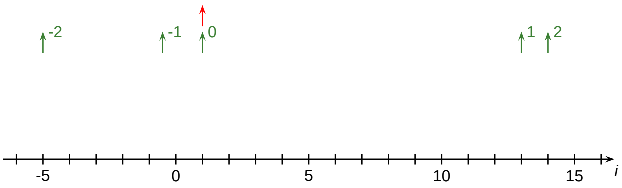

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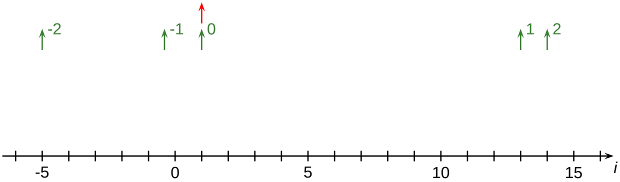

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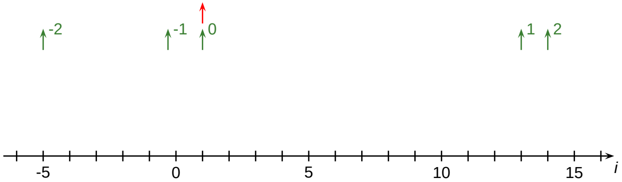

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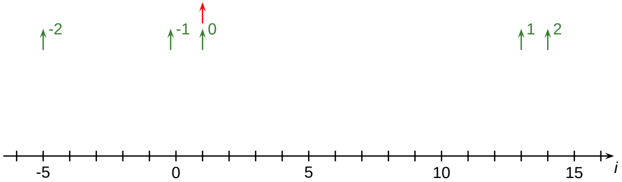

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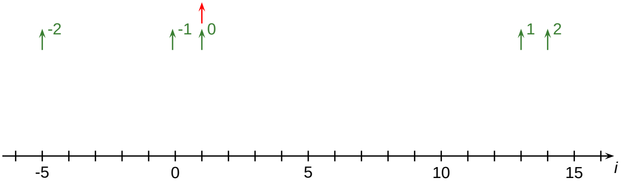

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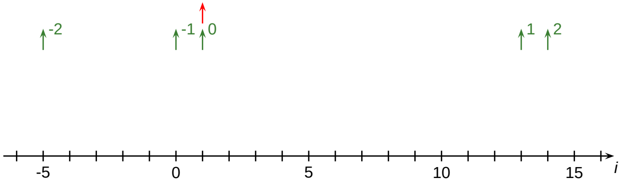

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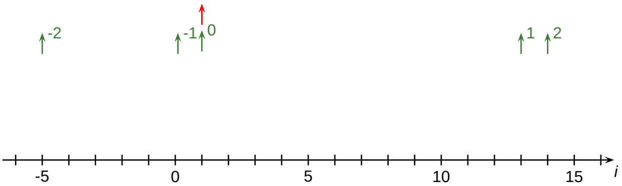

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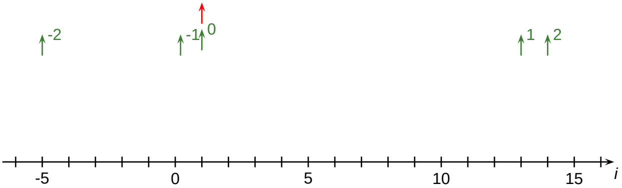

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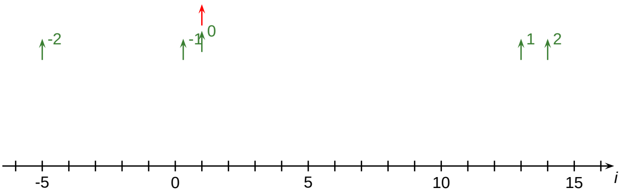

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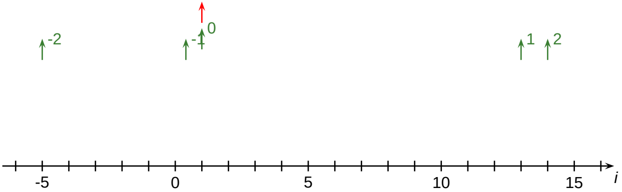

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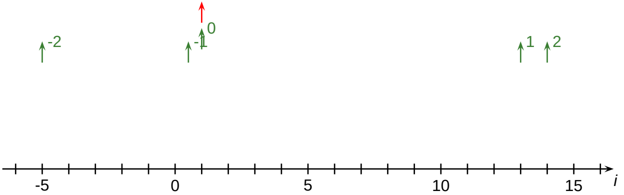

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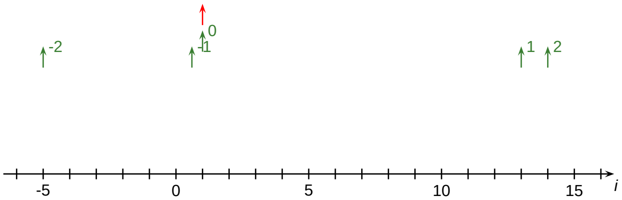

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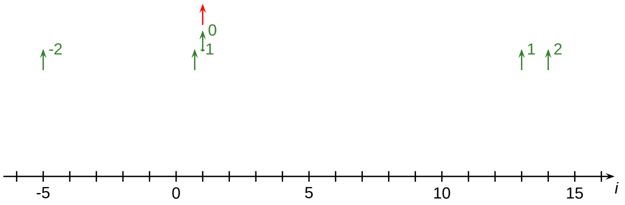

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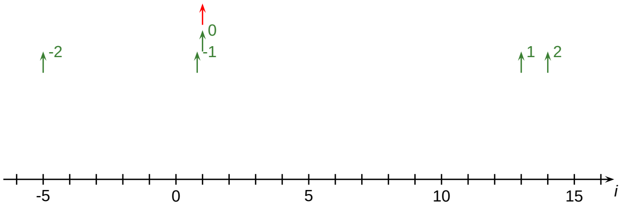

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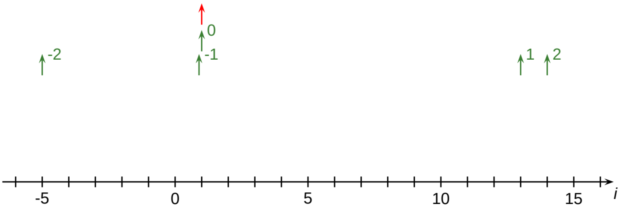

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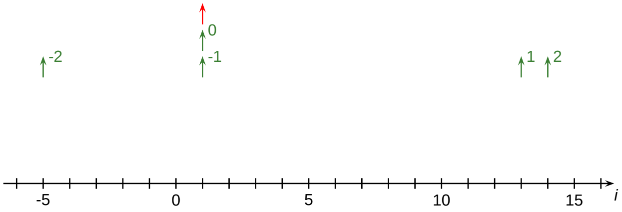

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$Q(t) \leq X(t)+$tight error

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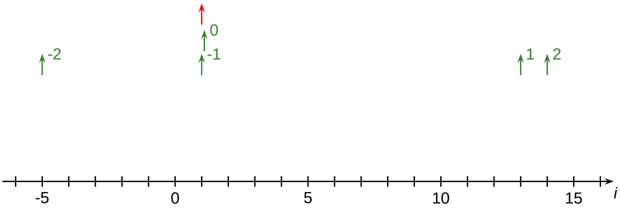
$m_Q(t) \leq 0 \Rightarrow Q(t) \leq X(t)$.



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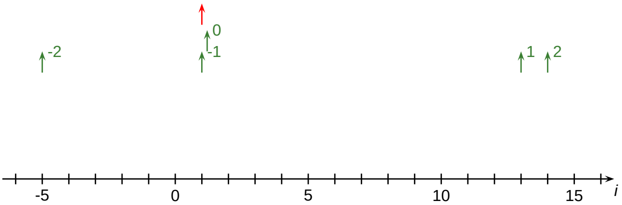

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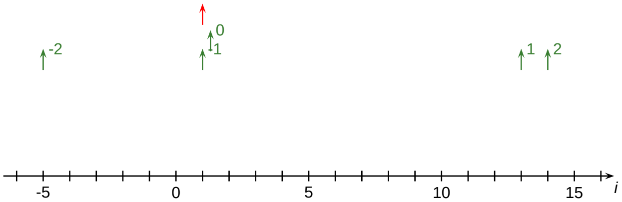

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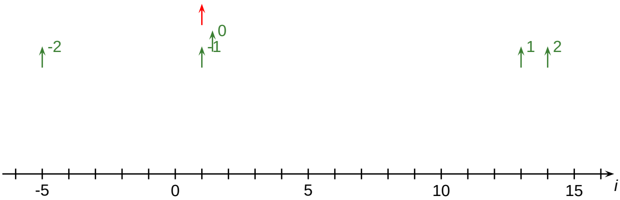

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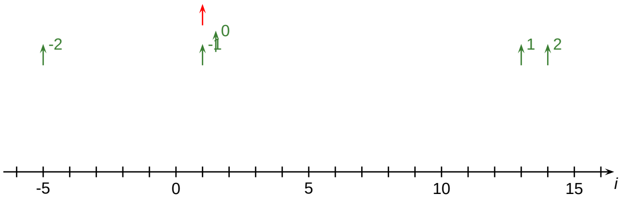

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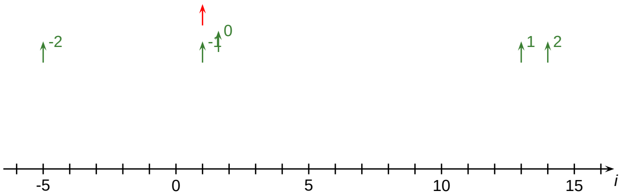

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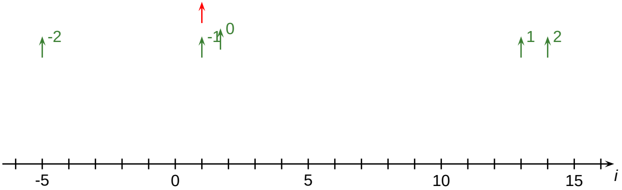

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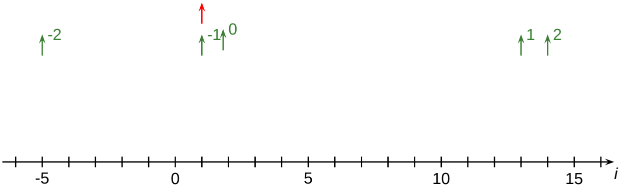

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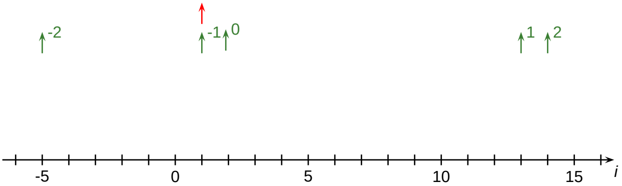

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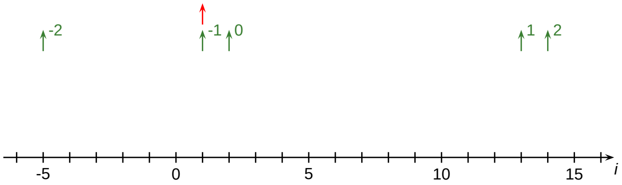

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This is the form of microscopic concavity we currently use: $m_Q(t)$ is dominated by a time-independent distribution with finite variance.

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Once this is done, we could proceed with less and less convex/concave models to see how $t^{1/3}$ scaling turns to $t^{1/4}$ for linear models (random average process, linear rate AZRP)...

Thank you.