

cases

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Denote  $p^{\min} := p^{\min\{0, v_2 + v_{11}\}}$   
 Denote  $\rho := (1 - p^{-1})$

## 1 Case 1

$$v_3 > v_1 \geq v_4 > v_2 \geq 0 \\ \Rightarrow v_{11} \geq -v_2 - v_1$$

$$\Rightarrow \alpha := \min\{v_2, v_2 + v_{11} + v_1\} = \begin{cases} v_2, & v_{11} \geq -v_1 \\ v_2 - 1, v_2 - 2, \dots, & v_{11} < -v_1 \end{cases}$$

For  $v_{11} \geq -v_2$ , we have  $p^{\min}\mu(a_{11})(1 + \alpha\rho) = p^{v_2}(1 + v_2\rho)$ .

For  $-v_1 \leq v_{11} \leq -v_2 - 1$ , we have  $p^{\min}\mu(a_{11})(1 + \alpha\rho) = \sum_{-v_1}^{-v_2-1} p^{v_2}\rho(1 + v_2\rho) = p^{v_2}\rho(v_1 - v_2)(1 + v_2\rho) = p^{v_2}\rho(v_1 - v_2) + p^{v_2}\rho^2 v_2(v_1 - v_2)$ .

For  $-v_2 - v_1 \leq v_{11} \leq -v_1 - 1$ , we have  $p^{\min}\mu(a_{11})(1 + \alpha\rho) = \sum_{-v_2-v_1}^{-v_1-1} p^{v_2}\rho(1 + \alpha\rho) = \sum_{i=1}^{v_2} p^{v_2}\rho(1 + (v_2 - i)\rho) = p^{v_2}v_2\rho + p^{v_2}v_2\rho^2 - p^{-v_2}\rho\binom{v_2+1}{2} = p^{v_2}v_2\rho + p^{v_2}\rho^2 - p^{v_2}\rho^2\binom{v_2+1}{2}$

So we have  $\sum_{v_{11} \geq -v_2 - v_1} = p^{v_2}(1 + v_2\rho + (v_1 - v_2)\rho + v_2(v_1 - v_2)\rho^2 + v_2\rho + v_2\rho^2 - \frac{(v_2+1)v_2}{2}\rho^2)$ . We compute the differences between  $v_1, v_2, v_3, v_4$ ,

$$v_3 \overset{d}{>} v_1 \overset{c}{\geq} v_4 \overset{b}{>} v_2 \overset{a}{\geq} 0$$

Thus, we substitute  $v_1 \rightarrow a + b + c$ ,  $v_2 \rightarrow a$ ,  $v_3 \rightarrow a + b + c + d$ ,  $v_4 \rightarrow a + b$ , and compute series with the new variables as indices, where  $a, c \geq 0$  and  $b, d \geq 1$ .

## 2 Case 2

$$v_1 \geq v_3 \\ v_1 \geq v_4 > v_2 \geq 0 \\ \Rightarrow v_{11} \geq -v_2 - v_3$$

$$\Rightarrow \alpha := \min\{v_2, v_2 + v_{11} + v_1\} = \begin{cases} v_2, & v_{11} \geq -v_1 \\ v_2 - 1, v_2 - 2, \dots, & v_{11} < -v_1 \end{cases}$$

We have two sub cases.

## 2.1 Sub case 2.1

$$-v_2 - v_3 \geq -v_1 \Rightarrow v_1 \geq v_2 + v_3$$

Here there is no phase transition, because the phase transition occurs at  $-v_1 - 1 < -v_2 - v_3 \leq v_{11}$

For  $v_{11} \geq -v_2$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = p^{v_2}(1 + v_2\rho)$ .

For  $-v_2 - v_3 \leq v_{11} \leq -v_2 - 1$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = \sum_{-v_2 - v_3}^{-v_2 - 1} p^{v_2} \rho(1 + v_2\rho) = p^{v_2} v_3 \rho(1 + v_2\rho) = p^{v_2} v_3 \rho + p^{v_2} v_3 v_2 \rho^2$ .

So we have  $\sum_{v_{11} \geq -v_2 - v_3} = p^{v_2}(1 + v_2\rho + v_3\rho + v_2 v_3 \rho^2)$ . We compute the differences between  $v_1, v_2, v_3, v_4$ , we have several arrangements,

$$1. \ v_1 \overset{d}{\geq} v_2 + v_3 \overset{e}{\geq} v_3 \overset{c}{\geq} v_4 \overset{b}{>} v_2 \overset{a}{\geq} 0$$

$$\text{But } e = v_2 + v_3 - v_3 = v_2 = a$$

Thus, we substitute  $v_1 \rightarrow 2a + b + c + d$ ,  $v_2 \rightarrow a$ ,  $v_3 \rightarrow a + b + c$ ,  $v_4 \rightarrow a + b$ , and compute series with the new variables as indices, where  $a, c, d \geq 0$  and  $b \geq 1$ .

$$2. \ v_1 \overset{d}{\geq} v_2 + v_3 \overset{c}{\geq} v_4 \overset{b}{>} v_3 \overset{a}{>} v_2 \overset{e}{\geq} 0$$

$$\text{But } v_2 + v_3 - c - b = v_3 \Rightarrow v_2 = v_2 + v_3 - v_3 = b + c$$

Thus, we substitute  $v_1 \rightarrow a + 2b + c + d$ ,  $v_2 \rightarrow b + c$ ,  $v_3 \rightarrow a + b + c$ ,  $v_4 \rightarrow a + 2b + c$ , and compute series with the new variables as indices, where  $c, d \geq 0$  and  $a, b \geq 1$ .

$$3. \ v_1 \overset{d}{\geq} v_2 + v_3 \overset{c}{\geq} v_4 \overset{b}{>} v_2 \overset{a}{\geq} v_3 \overset{e}{\geq} 0$$

$$\text{But } v_2 + v_3 - c - b = v_2 \Rightarrow v_3 = v_2 + v_3 - v_2 = b + c$$

Thus, we substitute  $v_1 \rightarrow a + 2b + c + d$ ,  $v_2 \rightarrow a + b + c$ ,  $v_3 \rightarrow b + c$ ,  $v_4 \rightarrow a + 2b + c$ , and compute series with the new variables as indices, where  $a, c, d \geq 0$  and  $b \geq 1$ .

## 2.2 Sub case 2.2

$$-v_2 - v_3 < -v_1 \Rightarrow v_1 < v_2 + v_3$$

For  $v_{11} \geq -v_2$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = p^{v_2}(1 + v_2\rho)$ .

For  $-v_1 \leq v_{11} \leq -v_2 - 1$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = \sum_{-v_1}^{-v_2 - 1} p^{v_2} \rho(1 + v_2\rho) = p^{v_2}(v_1 - v_2)\rho(1 + v_2\rho) = p^{v_2}(v_1 - v_2)\rho + p^{v_2}(v_1 - v_2)v_2\rho^2$ .

For  $-v_2 - v_3 \leq v_{11} \leq -v_1 - 1$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = \sum_{-v_2 - v_3}^{-v_1 - 1} p^{v_2} \rho(1 + \alpha\rho) = \sum_{i=1}^{v_2 + v_3 - v_1} p^{v_2} \rho(1 + (v_2 - i)\rho) = p^{v_2}(v_2 - v_3 + v_1)\rho + p^{v_2}(v_2 - v_3 + v_1)v_2\rho^2 - p^{v_2} \binom{v_2 + v_3 - v_1}{2} \rho^2$ .

So we have  $\sum_{v_{11} \geq -v_2 - v_3} = p^{v_2}(1 + v_2\rho + (v_1 - v_2)\rho + (v_1 - v_2)v_2\rho^2 + (v_2 - v_3 + v_1)\rho + (v_2 - v_3 + v_1)v_2\rho^2 - \frac{(v_2 - v_3 + v_1 + 1)(v_2 - v_3 + v_1)}{2} \rho^2)$ . We compute the differences between  $v_1, v_2, v_3, v_4$ , we have several arrangements,

$$1. v_2 + v_3 \overset{d}{>} v_1 \overset{c}{\geq} v_3 \overset{b}{\geq} v_4 \overset{a}{>} v_2 \overset{e}{\geq} 0$$

But  $c = v_1 - v_3$  and  $d = v_2 + v_3 - v_1$ , so  $e = v_2 = c + d$

Thus, we substitute  $v_1 \rightarrow a + b + 2c + d$ ,  $v_2 \rightarrow c + d$ ,  $v_3 \rightarrow a + b + c + d$ ,  $v_4 \rightarrow a + c + d$ , and compute series with the new variables as indices, where  $b, c \geq 0$  and  $a, d \geq 1$ .

$$2. v_2 + v_3 \overset{d}{>} v_1 \overset{c}{\geq} v_4 \overset{b}{>} v_3 \overset{a}{>} v_2 \overset{e}{\geq} 0$$

But  $v_2 + v_3 - d - c - b = v_3 \Rightarrow b + c + d = v_2 + v_3 - v_3 = v_2$

Thus, we substitute  $v_1 \rightarrow a + 2b + 2c + d$ ,  $v_2 \rightarrow b + c + d$ ,  $v_3 \rightarrow a + b + c + d$ ,  $v_4 \rightarrow a + 2b + c + d$ , and compute series with the new variables as indices, where  $c \geq 0$  and  $a, b, d \geq 1$ .

$$3. v_2 + v_3 \overset{d}{>} v_1 \overset{c}{\geq} v_4 \overset{b}{>} v_2 \overset{a}{\geq} v_3 \overset{e}{\geq} 0$$

But  $v_2 + v_3 - d - c - b = v_2 \Rightarrow v_3 = v_2 + v_3 - v_2 = b + c + d$

Thus, we substitute  $v_1 \rightarrow a + 2b + 2c + d$ ,  $v_2 \rightarrow a + b + c + d$ ,  $v_3 \rightarrow b + c + d$ ,  $v_4 \rightarrow a + 2b + c + d$ , and compute series with the new variables as indices, where  $a, c \geq 0$  and  $b, d \geq 1$ .

### 3 Case 3

$$v_4 > v_3 > v_1 \geq 0$$

$$v_4 > v_2 \geq 0$$

$$\Rightarrow v_{11} \geq -v_2 - v_1$$

$$\Rightarrow \alpha := \min\{v_2, v_2 + v_{11} + v_4\} = \begin{cases} v_2, & v_{11} \geq -v_4 \\ v_2 - 1, v_2 - 2, \dots, & v_{11} < -v_4 \end{cases}$$

We have two sub cases

#### 3.1 Sub case 3.1

$$-v_2 - v_1 \geq -v_4 \Rightarrow v_2 + v_1 \leq v_4$$

There is no phase transition here, since  $v_{11} \geq -v_2 - v_1 \geq -v_4$

For  $v_{11} \geq -v_2$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = p^{v_2}(1 + v_2\rho)$ .

For  $-v_2 - v_1 \leq v_{11} \leq -v_2 - 1$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = \sum_{-v_2 - v_1}^{-v_2 - 1} p^{v_2} \rho(1 + v_2\rho) = p^{v_2} v_1 \rho + p^{v_2} v_1 v_2 \rho^2$ .

So we have  $\sum_{v_{11} \geq -v_2 + v_1} p^{\min} \mu(a_{11})(1 + \alpha\rho) = p^2(1 + v_2\rho + v_1\rho + v_1 v_2 \rho^2)$ .

We have several arrangements,

$$1. v_4 \overset{d}{\geq} v_1 + v_2 \overset{c}{\geq} v_3 \overset{b}{>} v_2 \overset{a}{>} v_1 \overset{e}{\geq} 0$$

But  $v_1 + v_2 - c - b = v_2 \Rightarrow v_1 = v_1 + v_2 - v_2 = b + c$

Thus, we substitute  $v_1 \rightarrow b + c$ ,  $v_2 \rightarrow a + b + c$ ,  $v_3 \rightarrow a + 2b + c$ ,  $v_4 \rightarrow a + 2b + 2c + d$ , and compute series with the new variables as indices, where  $c, d \geq 0$  and  $a, b \geq 1$ .

$$2. \ v_4 \stackrel{d}{\geq} v_1 + v_2 \stackrel{a}{\geq} v_2 \stackrel{c}{\geq} v_3 \stackrel{b}{>} v_1 \stackrel{a}{\geq} 0$$

We substitute  $v_1 \rightarrow a$ ,  $v_2 \rightarrow a + b + c$ ,  $v_3 \rightarrow a + b$ ,  $v_4 \rightarrow 2a + b + c + d$ , and compute series with the new variables as indices, where  $a, c, d \geq 0$  and  $b \geq 1$ .

### 3.2 Sub case 3.2

$$-v_2 - v_1 < -v_4 \Rightarrow v_2 + v_1 > v_4$$

For  $v_{11} \geq -v_2$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = p^{v_2}(1 + v_2\rho)$ .

For  $-v_4 \leq v_{11} \leq -v_2 - 1$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = \sum_{-v_4}^{-v_2-1} p^{v_2} \rho(1 + v_2\rho) = p^{v_2}(v_4 - v_2)\rho + p^{v_2}(v_4 - v_2)v_2\rho^2$ .

For  $-v_2 - v_1 \leq v_{11} \leq -v_4 - 1$ , we have  $p^{\min} \mu(a_{11})(1 + \alpha\rho) = \sum_{-v_2-v_1}^{-v_4-1} p^{v_2} \rho(1 + v_2\rho) = p^{v_2}(v_1 + v_2 - v_4)\rho + p^{v_2}(v_1 + v_2 - v_4)v_2\rho^2 - p^{v_2} \binom{v_1 + v_2 - v_4 + 1}{2} \rho^2$ .

So we have  $\sum_{v_{11} \geq -v_2 + v_1} p^{\min} \mu(a_{11})(1 + \alpha\rho) = p^2(1 + v_2\rho + (v_4 - v_2)\rho + (v_4 - v_2)v_2\rho^2 + (v_1 + v_2 - v_4)\rho + (v_1 + v_2 - v_4)v_2\rho^2 - \frac{(v_1 + v_2 - v_4 + 1)(v_1 + v_2 - v_4)}{2} \rho^2)$

We have several arrangements,

$$1. \ v_1 + v_2 \stackrel{d}{>} v_4 \stackrel{c}{\geq} v_3 \stackrel{b}{>} v_2 \stackrel{a}{>} v_1 \stackrel{e}{\geq} 0$$

But  $v_1 + v_2 - d - c - b = v_2 \Rightarrow v_1 = v_1 + v_2 - v_2 = b + c + d$

Thus, we substitute  $v_1 \rightarrow b + c + d$ ,  $v_2 \rightarrow a + b + c + d$ ,  $v_3 \rightarrow a + 2b + c + d$ ,  $v_4 \rightarrow a + 2b + 2c + d$ , and compute series with the new variables as indices, where  $c \geq 0$  and  $a, b, d \geq 1$

$$2. \ v_1 + v_2 \stackrel{d}{>} v_4 \stackrel{c}{\geq} v_2 \stackrel{b}{\geq} v_3 \stackrel{a}{>} v_1 \stackrel{e}{\geq} 0$$

But  $v_1 + v_2 - d - c = v_2 \Rightarrow v_1 = v_1 + v_2 - v_2 = c + d$

Thus, we substitute  $v_1 \rightarrow c + d$ ,  $v_2 \rightarrow a + b + c + d$ ,  $v_3 \rightarrow a + c + d$ ,  $v_4 \rightarrow a + b + 2c + d$ , and compute series with the new variables as indices, where  $b \geq 0$  and  $a, c, d \geq 1$

$$3. \ v_1 + v_2 \stackrel{d}{>} v_4 \stackrel{c}{\geq} v_3 \stackrel{b}{>} v_1 \stackrel{a}{\geq} v_2 \stackrel{e}{\geq} 0$$

But  $v_1 + v_2 - d - c - b = v_1 \Rightarrow v_2 = v_1 + v_2 - v_1 = b + c + d$

Thus, we substitute  $v_1 \rightarrow a + b + c + d$ ,  $v_2 \rightarrow b + c + d$ ,  $v_3 \rightarrow a + 2b + c + d$ ,  $v_4 \rightarrow a + 2b + 2c + d$ , and compute series with the new variables as indices, where  $a \geq 0$  and  $b, c, d \geq 1$