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函子范畴的 incidence 代数的两个例子

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摘要: 以箭图 Q_1, Q_2, Q_3 为例,构造有限偏序 k 范畴 Γ_1, Γ_2,考虑 Γ_1, Γ_2 及函子范畴 $\Gamma_1^{\Gamma_2}$ 诱导的 incidence 代数的两个例子。

关键词: 函子范畴; Incidence 代数; 同构

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Two examples of incidence algebra of the functor category

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Abstract: Taking the quivers Q_1, Q_2, Q_3 as an example, finite partially ordered k-category Γ_1, Γ_2 were constructed. Two examples of incidence algebra induced by Γ_1, Γ_2 and functor category $\Gamma_1^{\Gamma_2}$ were considered.

Keywords: functor category; incidence algebra; isomorphism

在范畴理论中,函子是用来研究范畴之间的对应关系,以两个范畴间的函子为对象,函子间的自然变换为态射的范畴称为函子范畴。许多常见的范畴是函子范畴,如常见的 G-集范畴是函子范畴[1],而且任意给定范畴可嵌入一个函子范畴。偏序集是联系代数、拓扑、逻辑等众多分支的一类重要数学对象,偏序集在表示论发展中占据重要地位[2]。incidence 代数是定义在有限偏序集上的一类代数,多年来, incidence 代数一直是代数学研究领域的热点之一[3]。本文探讨箭图诱导的 incident 代数, 得到关于 incident 代数维数的一个结果与一个猜想。

1 预备知识

为引用方便,对重要的相关定义作简要的回顾。

定义 1 设 $\mathscr{C}$ 是一个小范畴, $\mathscr{D}$ 是范畴,定义范畴 $\mathscr{D}^{\mathscr{C}}$(称之为函子范畴): $\mathrm{obj}\mathscr{D}^{\mathscr{C}} = \{T \mid T:\mathscr{C} \to \mathscr{D}$ 为共变函子$\}$, $\mathrm{Hom}_{\mathscr{D}^{\mathscr{C}}}(T,T') = \{\tau: T \to T'$ 为自然变换$\}$, 合成是自然变换的合成。

定理 1[4] 设 k 是有单位元 1 的交换环,范畴 $\mathscr{C}$ 为小范畴,若范畴 $\mathscr{D}$ 是 k 上小范畴,则函子范畴 $\mathscr{D}^{\mathscr{C}}$ 仍为 k 上小范畴。

2 两个例子

例 1 设 k 是有单位元 1 的交换环,

构造箭图 $Q_1: a\cdot \underset{\beta}{\overset{\alpha}{\rightleftarrows}} \cdot b$, $I = <\alpha\beta, \beta\alpha>$ $\Leftrightarrow \alpha\beta = 0, \beta\alpha = 0$, 构造箭图 $Q_2: 1\cdot \xrightarrow{l} \cdot 2$, $kQ_1 = ke_a + ke_b + k\alpha + k\beta$, $kQ_2 = ke_1 + ke_2 + kl$, 记 $\Gamma_1 = kQ_1 - \mathrm{mod}$, $\Gamma_2 = kQ_2 - \mathrm{mod}$, 那么 Γ_1, Γ_2 是 k 上小范畴,且同构于箭图 Q (图 1)诱导的 10 维代数的模范畴, 其中, $\gamma\delta = 0, \delta\gamma = 0, \eta\tau = 0, \tau\eta = 0$, $\gamma\varepsilon = 0$, $\varepsilon\tau = 0, \eta\sigma = 0, \delta\eta = 0$。

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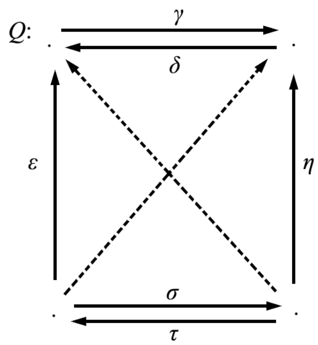

图 1 Kronecker 箭图与 A_2 箭图诱导的 incidence 代数

Fig.1　Incidence algebra induced by Kronecker quiver and A_2 quiver

证明：箭图 Q_1 可视为范畴 Γ_1：obj：a,b,α,β，mor：$\mathrm{Hom}(a,b)=<\alpha>$，$\mathrm{Hom}(b,a)=<\beta>$，$\mathrm{Hom}(a,a)=<e_\alpha>$，$\mathrm{Hom}(b,b)=<e_\beta>$。

箭图 Q_2 可视为范畴 Γ_2：obj：1,2，mor：$\mathrm{Hom}(1,1)=<e_1>$，$\mathrm{Hom}(2,2)=<e_2>$，$\mathrm{Hom}(1,2)=<l>$。

显然，Γ_1，Γ_2 都是 k 上小范畴。根据定理 1，$\Gamma_1^{\Gamma_2}$ 也是 k 上小范畴：obj：F_1,F_2,F_3,F_4，mor：$\mathrm{Hom}(F_1,F_1)=<ke_{F_1}>$，$\mathrm{Hom}(F_2,F_2)=<ke_{F_2}>$，$\mathrm{Hom}(F_3,F_3)=<ke_{F_3}>$，$\mathrm{Hom}(F_4,F_4)=<ke_{F_4}>$，$\mathrm{Hom}(F_1,F_2)=<k\gamma>$，$\mathrm{Hom}(F_2,F_1)=<k\delta>$，$\mathrm{Hom}(F_3,F_1)=<k\varepsilon>$，$\mathrm{Hom}(F_4,F_2)=<k\eta>$，$\mathrm{Hom}(F_3,F_4)=<k\sigma>$，$\mathrm{Hom}(F_2,F_1)=<k\tau>$。

具体地，有：

obj：$F_1:\Gamma_2\to\Gamma_1:F_1(1)=a,F_1(2)=b,F_1(l)=\alpha,F_1(e_1)=e_a,F_1(e_2)=e_b$，$F_2:\Gamma_2\to\Gamma_1:F_2(1)=b,F_2(2)=a,F_2(l)=\beta,F_2(e_1)=e_b,F_2(e_2)=e_a$，$F_3:\Gamma_2\to\Gamma_1:F_3(1)=a,F_3(2)=a,F_3(l)=e_a,F_3(e_1)=e_a,F_3(e_2)=e_b$，$F_4:\Gamma_2\to\Gamma_1:F_4(1)=b,F_4(2)=b,F_4(l)=e_b,F_4(e_1)=e_a,F_4(e_2)=e_b$。

mor：$e_{F_1}:F_1\to F_1$，$e_{F_2}:F_2\to F_2$，$e_{F_3}:F_3\to F_3$，$e_{F_4}:F_4\to F_4$，$\gamma=(\gamma_1,\gamma_2):F_1\to F_2$，$\delta=(\delta_1,\delta_2):F_2\to F_1$，$\varepsilon=(\varepsilon_1,\varepsilon_2):F_3\to F_1$，$\eta=(\eta_1,\eta_2):F_4\to F_2$，$\sigma=(\sigma_1,\sigma_2):F_3\to F_4$，$\tau=(\tau_1,\tau_2):F_4\to F_3$ 满足函子交换图（图 2）如下。

$$\begin{array}{ccc} F_1(1) & \to & F_2(1) \\ \downarrow & & \downarrow \\ F_1(2) & \to & F_2(2) \end{array}$$
$\gamma:F_1\to F_2$ 函子交换图

$$\begin{array}{ccc} F_2(1) & \to & F_1(1) \\ \downarrow & & \downarrow \\ F_2(2) & \to & F_1(2) \end{array}$$
$\delta:F_2\to F_1$ 函子交换图

$$\begin{array}{ccc} F_3(1) & \to & F_1(1) \\ \downarrow & & \downarrow \\ F_3(2) & \to & F_1(2) \end{array}$$
$\varepsilon:F_3\to F_1$ 函子交换图

$$\begin{array}{ccc} F_4(1) & \to & F_2(1) \\ \downarrow & & \downarrow \\ F_4(2) & \to & F_2(2) \end{array}$$
$\eta:F_4\to F_2$ 函子交换图

$$\begin{array}{ccc} F_3(1) & \to & F_4(1) \\ \downarrow & & \downarrow \\ F_3(2) & \to & F_4(2) \end{array}$$
$\sigma:F_3\to F_4$ 函子交换图

$$\begin{array}{ccc} F_4(1) & \to & F_3(1) \\ \downarrow & & \downarrow \\ F_4(2) & \to & F_3(2) \end{array}$$
$\tau:F_4\to F_3$ 函子交换图

图 2　模 $\gamma,\delta,\varepsilon,\eta,\sigma,\tau$ 的函子交换图

Fig. 2　Functor exchange graph of mor $\gamma,\delta,\varepsilon,\eta,\sigma,\tau$

$k\Gamma_1^{\Gamma_2}=ke_{F_1}+ke_{F_2}+ke_{F_3}+ke_{F_4}+k\gamma+k\delta+k\varepsilon+k\eta+k\sigma+k\tau$，故 $\Gamma_1^{\Gamma_2}$（图 3）同构于 Γ 诱导的 10 维代数的模范畴，其中 $\gamma\delta=0,\delta\gamma=0,\eta\tau=0,\tau\eta=0,\gamma\varepsilon=0,\varepsilon\tau=0,\eta\sigma=0,\delta\eta=0$。

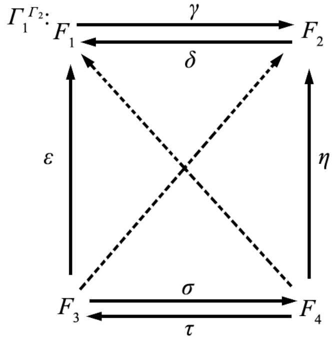

图 3　$\Gamma_1^{\Gamma_2}$ 范畴中对象关系图

Fig. 3　Objects' relation graph in category $\Gamma_1^{\Gamma_2}$

例 2 设 k 是有单位元 1 的交换环，

构造箭图 $Q_1:a\cdot \underset{\beta}{\overset{\alpha}{\rightleftarrows}}\cdot b$，$I=<\alpha\beta,\beta\alpha>$

$\Leftrightarrow\alpha\beta=0,\beta\alpha=0$，

构造箭图 $Q_3:1\cdot\xrightarrow{l}\cdot 2\xrightarrow{m}\cdot 3,ml\neq 0$，

$kQ_1=ke_a+ke_b+k\alpha+k\beta$，$kQ_3=ke_1+ke_2+ke_3+kl+km+k(ml)$，记 $\Gamma_1=kQ_1-\mathrm{mod}$，$\Gamma_3=kQ_3-\mathrm{mod}$，那么 $\Gamma_1^{\Gamma_3}$ 是 k 上小范畴，且同构于箭图 Q'（图 4）诱导的 24 维代数的模范畴，其中，$\alpha\beta=0,\beta\alpha=0,\gamma\delta=0,\delta\gamma=0,\varepsilon\eta=0,\eta\varepsilon=0,\theta\eta=0,\delta\theta=0,\mu\delta=0,\beta\mu=0,\lambda\varepsilon=0,\gamma\lambda=0,\nu\gamma=0,\alpha\nu=0$，且 $\mu\varepsilon_1=\alpha,\nu\eta_1=\beta,\theta\varepsilon_2=\gamma,\lambda\eta_2=\delta,\varepsilon_2\lambda=\eta,\sigma\varepsilon_2=\mu,\tau\eta_2=\nu$。

证明：类似例 1，箭图 Q_3 可视为范畴 Γ_3：obj：$1,2,3,m,l,ml$，mor：$\mathrm{Hom}(1,1)=<e_1>$，$\mathrm{Hom}(2,2)=<e_2>$，$\mathrm{Hom}(3,3)=<e_3>$，$\mathrm{Hom}(1,2)=<m>$，$\mathrm{Hom}(2,3)=<l>$，$\mathrm{Hom}(1,3)=<ml>$。

与例 1 同理可得 $\Gamma_1^{\Gamma_3}$ 也是 k 上小范畴：obj：F_1,F_2,F_3,F_4,F_5,F_6。

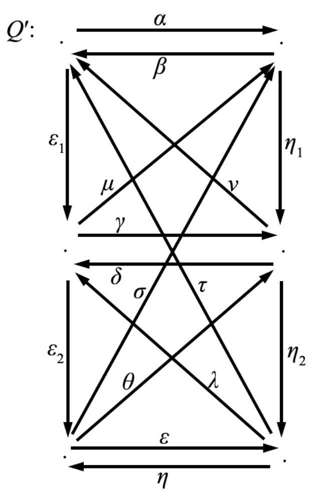

图 4　Kronecker 箭图与 A_3 箭图诱导的 incidence 代数

Fig.4　Incidence algebra induced by Kronecker quiver and A_3 quiver

mor: $\mathrm{Hom}(F_1,F_1) = <F_{11}>$, $\mathrm{Hom}(F_2,F_2) = <F_{22}>$, $\mathrm{Hom}(F_3,F_3) = <F_{33}>$, $\mathrm{Hom}(F_4,F_4) = <F_{44}>$, $\mathrm{Hom}(F_5,F_5) = <F_{55}>$, $\mathrm{Hom}(F_6,F_6) = <F_{66}>$, $\mathrm{Hom}(F_1,F_2) = <F_{12}>$, $\mathrm{Hom}(F_1,F_3) = <F_{13}>$, $\mathrm{Hom}(F_1,F_4) = <F_{14}>$, $\mathrm{Hom}(F_2,F_1) = <F_{21}>$, $\mathrm{Hom}(F_2,F_5) = <F_{25}>$, $\mathrm{Hom}(F_2,F_6) = <F_{26}>$, $\mathrm{Hom}(F_3,F_2) = <F_{32}>$, $\mathrm{Hom}(F_3,F_4) = <F_{34}>$, $\mathrm{Hom}(F_3,F_6) = <F_{36}>$, $\mathrm{Hom}(F_4,F_2) = <F_{42}>$, $\mathrm{Hom}(F_4,F_5) = <F_{45}>$, $\mathrm{Hom}(F_4,F_6) = <F_{46}>$, $\mathrm{Hom}(F_5,F_1) = <F_{51}>$, $\mathrm{Hom}(F_5,F_3) = <F_{53}>$, $\mathrm{Hom}(F_5,F_4) = <F_{54}>$, $\mathrm{Hom}(F_6,F_1) = <F_{61}>$, $\mathrm{Hom}(F_6,F_3) = <F_{63}>$, $\mathrm{Hom}(F_6,F_5) = <F_{65}>$。

具体地,有:

obj: $F_1:\Gamma_3 \to \Gamma_1: F_1(1) = a, F_1(2) = a, F_1(3) = a, F_1(l) = e_a, F_1(m) = e_a, F_1(ml) = e_a, F_1(e_1) = e_a, F_1(e_2) = e_a, F_1(e_3) = e_a$; $F_2:\Gamma_3 \to \Gamma_1: F_2(1) = b, F_2(2) = b, F_2(3) = b, F_2(l) = e_b, F_2(m) = e_b, F_2(ml) = e_b, F_2(e_1) = e_b, F_2(e_2) = e_b, F_2(e_3) = e_b$; $F_3:\Gamma_3 \to \Gamma_1: F_3(1) = a, F_3(2) = a, F_3(3) = b, F_3(l) = e_a, F_3(m) = \alpha, F_3(ml) = \alpha, F_3(e_1) = e_a, F_3(e_2) = e_a, F_3(e_3) = e_b$; $F_4:\Gamma_3 \to \Gamma_1: F_4(1) = a, F_4(2) = b, F_4(3) = b, F_4(l) = \alpha, F_4(m) = e_b, F_4(ml) = \alpha, F_4(e_1) = e_a, F_4(e_2) = e_b, F_4(e_3) = e_b$; $F_5:\Gamma_3 \to \Gamma_1: F_5(1) = b, F_5(2) = a, F_5(3) = a, F_5(l) = \beta, F_5(m) = e_a, F_5(ml) = \beta, F_5(e_1) = e_b, F_5(e_2) = e_a, F_5(e_3) = e_a$; $F_6:\Gamma_3 \to \Gamma_1: F_6(1) = b, F_6(2) = b, F_6(3) = a, F_6(l) = e_b, F_6(m) = \beta, F_6(ml) = \beta, F_6(e_1) = e_b, F_6(e_2) = e_b, F_6(e_3) = e_a$。

mor: $F_{11}:F_1 \to F_1$, $F_{22}:F_2 \to F_2$, $F_{33}:F_3 \to F_3$, $F_{44}:F_4 \to F_4$, $F_{55}:F_5 \to F_5$, $F_{66}:F_6 \to F_6$, $F_{12}:F_1 \to F_2$, $F_{13}:F_1 \to F_3$, $F_{14}:F_1 \to F_4$, $F_{21}:F_2 \to F_1$, $F_{25}:F_2 \to F_5$, $F_{26}:F_2 \to F_6$, $F_{32}:F_3 \to F_2$, $F_{34}:F_3 \to F_4$, $F_{36}:F_3 \to F_6$, $F_{42}:F_4 \to F_2$, $F_{45}:F_4 \to F_5$, $F_{46}:F_4 \to F_6$, $F_{51}:F_5 \to F_1$, $F_{53}:F_5 \to F_3$, $F_{54}:F_5 \to F_4$, $F_{61}:F_6 \to F_1$, $F_{63}:F_6 \to F_3$, $F_{65}:F_6 \to F_5$ 满足函子交换图(图 5)如下。

$$\begin{array}{ccc} F_1(1) & \to & F_2(1) \\ \downarrow & & \downarrow \\ F_1(2) & \to & F_2(2) \\ \downarrow & & \downarrow \\ F_1(3) & \to & F_2(3) \end{array}$$

$F_{12}:F_1 \to F_2$ 函子交换图

$$\begin{array}{ccc} F_1(1) & \to & F_3(1) \\ \downarrow & & \downarrow \\ F_1(2) & \to & F_3(2) \\ \downarrow & & \downarrow \\ F_1(3) & \to & F_3(3) \end{array}$$

$F_{13}:F_1 \to F_3$ 函子交换图

$$\begin{array}{ccc} F_1(1) & \to & F_4(1) \\ \downarrow & & \downarrow \\ F_1(2) & \to & F_4(2) \\ \downarrow & & \downarrow \\ F_1(3) & \to & F_4(3) \end{array}$$

$F_{14}:F_1 \to F_4$ 函子交换图

$$\begin{array}{ccc} F_2(1) & \to & F_1(1) \\ \downarrow & & \downarrow \\ F_2(2) & \to & F_1(2) \\ \downarrow & & \downarrow \\ F_2(3) & \to & F_1(3) \end{array}$$

$F_{21}:F_2 \to F_1$ 函子交换图

$$\begin{array}{ccc} F_2(1) & \to & F_5(1) \\ \downarrow & & \downarrow \\ F_2(2) & \to & F_5(2) \\ \downarrow & & \downarrow \\ F_2(3) & \to & F_5(3) \end{array}$$

$F_{25}:F_2 \to F_5$ 函子交换图

$$\begin{array}{ccc} F_2(1) & \to & F_6(1) \\ \downarrow & & \downarrow \\ F_2(2) & \to & F_6(2) \\ \downarrow & & \downarrow \\ F_2(3) & \to & F_6(3) \end{array}$$

$F_{26}:F_2 \to F_6$ 函子交换图

$$\begin{array}{ccc} F_3(1) & \to & F_2(1) \\ \downarrow & & \downarrow \\ F_3(2) & \to & F_2(2) \\ \downarrow & & \downarrow \\ F_3(3) & \to & F_2(3) \end{array}$$

$F_{32}:F_3 \to F_2$ 函子交换图

$$\begin{array}{ccc} F_3(1) & \to & F_4(1) \\ \downarrow & & \downarrow \\ F_3(2) & \to & F_4(2) \\ \downarrow & & \downarrow \\ F_3(3) & \to & F_4(3) \end{array}$$

$F_{34}:F_3 \to F_4$ 函子交换图

$$\begin{array}{ccc} F_3(1) & \to & F_6(1) \\ \downarrow & & \downarrow \\ F_3(2) & \to & F_6(2) \\ \downarrow & & \downarrow \\ F_3(3) & \to & F_6(3) \end{array}$$

$F_{36}:F_3 \to F_6$ 函子交换图

$$\begin{array}{ccc} F_4(1) & \to & F_2(1) \\ \downarrow & & \downarrow \\ F_4(2) & \to & F_2(2) \\ \downarrow & & \downarrow \\ F_4(3) & \to & F_2(3) \end{array}$$

$F_{42}:F_4 \to F_2$ 函子交换图

$$\begin{array}{ccc} F_4(1) & \to & F_5(1) \\ \downarrow & & \downarrow \\ F_4(2) & \to & F_5(2) \\ \downarrow & & \downarrow \\ F_4(3) & \to & F_5(3) \end{array}$$

$F_{45}:F_4 \to F_5$ 函子交换图

$$\begin{array}{ccc} F_4(1) & \to & F_6(1) \\ \downarrow & & \downarrow \\ F_4(2) & \to & F_6(2) \\ \downarrow & & \downarrow \\ F_4(3) & \to & F_6(3) \end{array}$$

$F_{46}:F_4 \to F_6$ 函子交换图

$$\begin{array}{ccc} F_5(1) & \to & F_1(1) \\ \downarrow & & \downarrow \\ F_5(2) & \to & F_1(2) \\ \downarrow & & \downarrow \\ F_5(3) & \to & F_1(3) \end{array}$$

$F_{51}:F_5 \to F_1$ 函子交换图

$$\begin{array}{ccc} F_5(1) & \to & F_3(1) \\ \downarrow & & \downarrow \\ F_5(2) & \to & F_3(2) \\ \downarrow & & \downarrow \\ F_5(3) & \to & F_3(3) \end{array}$$

$F_{53}:F_5 \to F_3$ 函子交换图

$$\begin{tikzcd} F_5(1) \arrow[r] \arrow[d] & F_4(1) \arrow[d] \\ F_5(2) \arrow[r] \arrow[d] & F_4(2) \arrow[d] \\ F_5(3) \arrow[r] & F_4(3) \end{tikzcd} \qquad \begin{tikzcd} F_6(1) \arrow[r] \arrow[d] & F_1(1) \arrow[d] \\ F_6(2) \arrow[r] \arrow[d] & F_1(2) \arrow[d] \\ F_6(3) \arrow[r] & F_1(3) \end{tikzcd}$$

$F_{54}: F_5 \rightarrow F_4$ 函子交换图　　$F_{61}: F_6 \rightarrow F_1$ 函子交换图

$$\begin{tikzcd} F_6(1) \arrow[r] \arrow[d] & F_3(1) \arrow[d] \\ F_6(2) \arrow[r] \arrow[d] & F_3(2) \arrow[d] \\ F_6(3) \arrow[r] & F_3(3) \end{tikzcd} \qquad \begin{tikzcd} F_6(1) \arrow[r] \arrow[d] & F_5(1) \arrow[d] \\ F_6(2) \arrow[r] \arrow[d] & F_5(2) \arrow[d] \\ F_6(3) \arrow[r] & F_5(3) \end{tikzcd}$$

$F_{63}: F_6 \rightarrow F_3$ 函子交换图　　$F_{65}: F_6 \rightarrow F_5$ 函子交换图

图 5　$F_{ij}: F_i \rightarrow F_j (i=1,\cdots 6,)$ 的函子交换图

Fig. 5　Functor exchange graph of mor $F_{ij}: F_i \rightarrow F_j (i=1,\cdots 6,)$

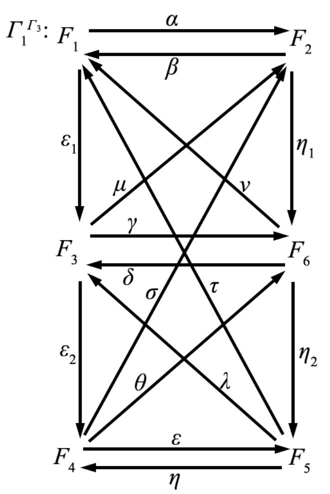

图 6　$\Gamma_1^{\Gamma_3}$ 中对象关系图

Fig. 6 Objects' relation graph in category $\Gamma_1^{\Gamma_3}$

故 $\Gamma_1^{\Gamma_3}$(图 6)同构于 Q' 诱导的 24 维代数的模范畴。其中，$\alpha\beta = 0, \beta\alpha = 0, \gamma\delta = 0, \delta\gamma = 0, \varepsilon\eta = 0, \eta\varepsilon = 0, \theta\eta = 0, \delta\theta = 0, \mu\delta = 0, \beta\mu = 0, \lambda\varepsilon = 0, \gamma\lambda = 0, \nu\gamma = 0, \alpha\nu = 0$。

注 1：若 $\mathscr{P}_1, \mathscr{P}_2$ 均为有限偏序 k - 范畴，记由范畴 $\mathscr{P}_1, \mathscr{P}_2$，函子范畴 $\mathscr{P}_1^{\mathscr{P}_2}$ 诱导的 incidence 代数分别为 A、B、C，$\mathscr{P}_1$，$\mathscr{P}_2$ 的点数分别记为 $|\mathscr{P}_1|, |\mathscr{P}_2|$。

根据例 1 得到：$\dim_k C = \dim_k A \times |\mathscr{P}_2| + |\mathscr{P}_1| \times (\dim_k B - |\mathscr{P}_2|)$，而根据例 2 有：
$\dim_k C = 24 \neq \dim_k A \times |\mathscr{P}_2| + |\mathscr{P}_1| \times (\dim_k B - |\mathscr{P}_2|) = 4\times3+2\times(6-3) = 18$。

注 2：设 $Q_1 = A_2$ 箭图，$Q_2 = A_n$ 箭图，令 $A = kQ_1, B = kQ_2, C = k(Q_1^{Q_2})$，则有：
$\dim_k C = \dim_k A \times |\mathscr{P}_1| + |\mathscr{P}_1| \times (\dim_k B + 1 - |\mathscr{P}_2|)$。由此，我们大胆猜想以上结论对其它情况可能也成立，有待进一步考究证明。

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