

Gorenstein Fano 3-fold

4/13/96 (Sat)

§1 X is a 3-fold with only Gorenstein canonical singularities.

X is Fano $\stackrel{\text{def}}{\iff} -K_X$ is ample

$\Rightarrow \exists S \in |-K_X|$ anticanonical divisor
(Shokurov, Reid) with only RDP's. S is K3.

$\Rightarrow |-K_X|$ is very ample with few exceptions

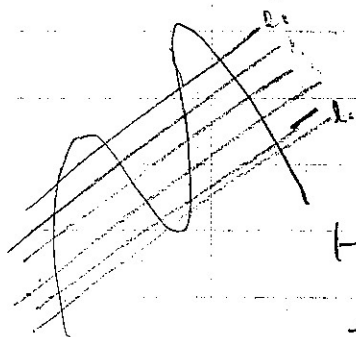
$\Rightarrow$ The image $\Phi_{-K_X}: X_{2g-2} \hookrightarrow \mathbb{P}^{g+1}$, called the anti-canonical model, is a projective variety with canonical curve section

$$\begin{cases} g = \frac{(-K_X)^3}{2} + 1 \\ \dim H^0(X, -K_X) = g+1 \\ (R-R + \text{Venus}) \end{cases}$$

$$\begin{array}{ccc} \text{a.c. model} & X_{2g-2} & \subset \mathbb{P}^{g+1} \\ & \downarrow & \downarrow \\ \text{proj. model of} & X_{\cap H} = S_{2g-2} & \subset \mathbb{P}^3 \\ \text{pt. RDP K3} & & \\ & \downarrow & \downarrow \\ \text{canonical model} & X_{\cap H \cap H'} = C_{2g-2} & \subset \mathbb{P}^{g+1} \\ \text{of smooth curve} & & \end{array}$$

§2 Example 1. Anticanonical model of $\text{Bl}_C \mathbb{P}^3$

a) $C_6 \subset \mathbb{P}^3$ smooth general rational curve of degree 6



$$\begin{array}{ccc} \uparrow & \uparrow \pi & \\ E \subset \text{Bl}_C \mathbb{P}^3 = Y & & -K_Y = 4\pi^*H - E \\ & & (-K_Y)^3 = 14 \end{array}$$

$|K_Y|$ is free and gives map $\Phi_{-K_Y}: Y \rightarrow \mathbb{P}^9$

There exists 6 - 4 secant lines $l_1, \dots, l_6$.

Let $Z_1, \dots, Z_6$ be plane strict transforms on Y .

Φ_{-K_Y} is an isomorphism outside $Z_1, \dots, Z_6$.

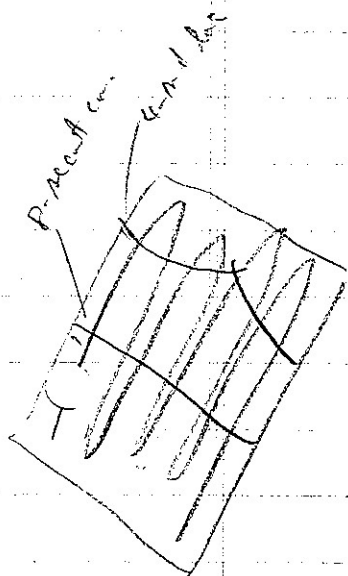
On the other hand, $(-K_Y \cdot Z_i) = 0$. Z_i 's are contracted to ODPs. The image X_{nc} of Φ_{-K_Y} is Fano 3-fold of genus 8 with 8 ODPs.

b) $C_{10} \subset \mathbb{P}^3$ degree 10, genus 12

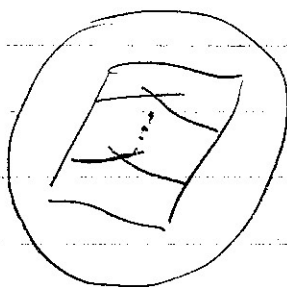
$$-K_Y = 4\pi^*H - E, \quad (-K_Y)^3 = 6, \quad (-K_Y) \text{ free}$$

$$(\# \text{ of } 4\text{-secant lines}) = 10.$$

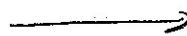
C_{10} has 1-dim'd family of 8-secant conics.



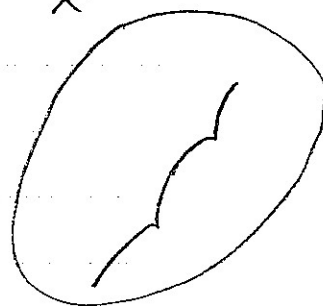
Y



$\Phi_{|-K_Y|}$



X



These strict transforms are contracted by $\Phi_{|-K_Y|}$.

The anticanonical model X has canonical singularities along a curve.

c) $C_{12} = S_3 \cap S_4 \subset \mathbb{P}^3$ The anticanonical model X of Y

is a quartic with a triple point. The strict transform of

S_3 is contracted to the isolated can. singularity.

~~Def. 1.1~~

Basic Example 2 Homogeneous variety of index $n-2$

$$\Sigma^n = G/P \subset \mathbb{P}(V) \quad \left\{ \begin{array}{l} G: \text{semi-simple alg. grp} \\ V: \text{fundamental representation} \\ X: \text{orbit of h.w. vector} \end{array} \right.$$

$\cong$ 4 homogeneous projective variety with $-K_\Sigma = (n-2)H$

$g = \frac{1}{2} \deg \Sigma + 1$	$n = \dim \Sigma$	G	V	
7	10	$SO(10)$	16-dim	half-spin representation
8	8	$SL(6)$	$\mathbb{A}^6$	$G(2,6) \subset \mathbb{P}^{14}$ 8-dim. Grassmannian
9	6	$Sp(3)$	14-dim	compact dual of Hy_3
10	5	Exp. type G_2	14-dim	adjoint rep.

$X = \sum_{i=1}^n H_{i,1} \cap \dots \cap H_{i,n-2}$ is Gorenstein Fano 3-fold of genus g if $\dim X = 3$.

We call these Fano 3-fold of linear section type.

§ 3 Main Theorem

Def. $-K_X \sim A_1 + A_2$ is a movable decomposition if both A_i are movable Weil divisors, i.e., $\dim |A_i| > 0$.

A Fano 3-fold X is indecomposable if $-K_X$ has no

movable decompositions.

Remark If X is smooth, then indecomposable
 $\Leftrightarrow$ Pic X is generated by $-K_X$ (Implication " $\Rightarrow$ " is not easy).

Theorem Let X be an indecomposable Fano 3-fold of genus g .

[A] Genus bound: $g \leq 10$ or $g = 12$.

[B] Description for $g \leq 10$: X is isomorphic to one of the following:

$$g=2 \quad X \xrightarrow{2:1} \mathbb{P}^3 \quad \deg(\text{Branch}) = 8$$

$$g=3 \quad X_4 \subset \mathbb{P}^4 \simeq X \xrightarrow{2:1} Q_3 \subset \mathbb{P}^4$$

$$g=4 \quad X_6 = (2) \cap (3) \subset \mathbb{P}^5$$

$$g=5 \quad X_8 = (2) \cap (2) \cap (2) \subset \mathbb{P}^6$$

$$g=6 \quad X_{10} = (2) \cap V_5^4 \subset \mathbb{P}^7 \quad V_5^4 \subset \mathbb{P}^7 \text{ smooth or cone over smooth } V_5^3 \subset \mathbb{P}^6$$

$$g=7, 8, 9, 10 \quad X \simeq \sum_{2g-2}^n H_1 \cap \dots \cap H_{n-3} \quad \text{linear section type}$$

[C] If $g=12$, then X is smooth and Pic X is generated by $-K_X$. Moreover, $X \cong G(3, 7, V)$

for 3-dim subspace $N \subset (\wedge^2 \mathbb{C}^7)^*$.

$$N = \langle \sigma_1, \sigma_2, \sigma_3 \rangle_{\mathbb{C}} \quad \sigma_i : \mathbb{C}^7 \times \mathbb{C}^7 \longrightarrow \mathbb{C}$$

skew-symmetric

$$G(3, 7, N) = \left\{ U \mid \begin{array}{l} \text{3-dim. subspace of } \mathbb{C}^7 \text{ which are} \\ \text{totally isotropic w.r.t. } \sigma_i, i=1,2,3 \end{array} \right\}$$

$$\cap \\ G(3, 7) \quad \text{12-dim. Grassmannian}$$

Remark Fermi 3-fold of genus 12 has two other descriptions. One is

$$VSP(F_4, 6) = \left\{ ([f_1], \dots, [f_6]) \mid \sum_{i=1}^6 f_i^4 = F_4 \right\}$$

where $F_4 = F_4(x, y, z)$ and f_i 's are linear forms.

§4 Consistency of indecomposability

Def. A ~~given~~ ^{smooth} polarized K3 surface (S, h) is

Petri general if, for every $h \sim a+b$, (see of Weil def)

$$i) \quad h^0(\mathcal{O}_S(a)) \cdot h^0(\mathcal{O}_S(b)) \leq g, \text{ and}$$

$$ii) \quad \mu: H^0(\mathcal{O}_S(a)) \otimes H^0(\mathcal{O}_S(b)) \longrightarrow H^0(\mathcal{O}_S(h))$$

is injective.

Lemma f not injective $\Rightarrow \dim \text{End}(E) \geq 2$

Take nonzero $f: E \rightarrow E$ which is not an isomorphism.

$\text{Im } f$ and $\text{Coker } f$ are quotients of E . Hence they are generated by global sections in each one. They are not trivial since $H^0(E, 0) = 0$. Hence

$$h^0(\det \text{Im } f) \geq 2 \quad \text{and} \quad h^0(\det \text{Coker } f) \geq 2$$

$\xrightarrow{\quad \text{defined as Weil div.} \quad}$

$$-K_X \sim \det E, \sim \det \text{Im } f + \det \text{Coker } f \quad \times$$

movable decomposition

□

Remark By similar argument, one can show

$C = X \cap H \cap H'$ is numerically general,

that is $h^0(\xi) h^0(K_C \xi^{-1}) \leq g$ for every $\xi \in \text{Pic } C$.

§5 Linear section theorem for K3 surfaces

(S.h) polarized RDP K3 surface $g = \frac{(h^2)}{2} + 1$

Assume (S.h) (or its resolution) is Petri general.

The following is easy to show.

Proposition $g=2$ $S \xrightarrow{2:1} \mathbb{P}^2$

$g=3$ $S_4 \subset \mathbb{P}^3$ $g=4$ $S_6 = (2) \cap (3)$ $g=5$ $S_8 = (2) \cap (2) \cap (2)$

($\Rightarrow$ Thm ⑤ $g=2, 3, 4, 5$)

Theorem ① (i) $g=7, 8, 9, 10$ $\left\{ \begin{array}{l} S \cong \sum^n \cap H_1 \cap \dots \cap H_{n-2} \\ (S, h) \text{ is of linear section type, i.e., } h = (\text{hyperplane section}) \end{array} \right.$

(ii) $g=12$, $\exists N \in (H^2(\mathbb{C}^7))^*$ $S \cong G(V, 3, N) \cap H$

Proved by Grassmannian embedding

$S \xrightarrow{2} C \in |h|$ smooth member.

Take $\xi \in \text{Pic } C$ with $h^0(\xi) = r$, $h^0(\xi) = s$ and $rs = g$

g	8	9	10	12
(r, s)	$(2, 4)$	$(3, 3)$	$(2, 5)$	$(3, 4)$
			$(\alpha_{(3, 2)})$	$(\alpha_{(2, 5)})$

Define vector bundle E_n on S by the exact seq.

$$0 \longrightarrow E_n^\vee \longrightarrow \mathcal{O}_S^{\oplus n} \longrightarrow \pi_* \xi \longrightarrow 0$$

$\uparrow$ sheaf supported on C

$$\det E_n \cong \mathcal{O}_S(h)$$

$$h^0(E_n) = r + s$$

$$\Phi_{E_n} : S \longrightarrow G(H^0(E_n), r)$$

g -dim. Grassmannian.

Ex. $g=8$ E_2 rank 2 curve of degree 8

$$S \longrightarrow G(2,6)$$

$$\begin{array}{ccc} H^1 & \cap & \cap \\ & \mathbb{P}^2 & \longrightarrow \mathbb{P}^{14} \end{array} \quad \text{Plucker}$$

is Porteous ($\Rightarrow$ Theorem.)

§6 Proof of Theorem B and C

$$\begin{array}{ccc} S & \subset & X \\ k3 & & \text{Fano} \end{array}$$

rank.
 $g=7$ We can twist
 curve bundle
 $\mathcal{N}_{S/\mathbb{P}^7}(2)$
 of $S \subset \mathbb{P}^7$ to embed
 S into Grassmann
 $nk=5$ $h^0=10$

By Th. ①, S is a linear section of Σ_{2g-2} .

$$\begin{array}{ccc} i: S & \hookrightarrow & \Sigma_{2g-2} \\ \cap & & \\ X & & \end{array}$$

$$\mathcal{O}_X(S) = \mathcal{O}_X(-K_X) =: \mathcal{O}(1)$$

(a morphism $j: \hat{S}_X \rightarrow \Sigma$ of)

Step 1. i extends to the formal nbd $\hat{S}_X$ of $S \subset X$.

① By Bott vanishing, $H^i(S, (\mathbb{Z}^* T_\Sigma)(-n)) = 0 \quad \forall n \geq 1$.

Step 2.

$$j^* \text{ induces } H^0(\mathcal{O}_\Sigma(1)) \xrightarrow{j^*} H^0(\hat{S}_X, \mathcal{O}(1))$$

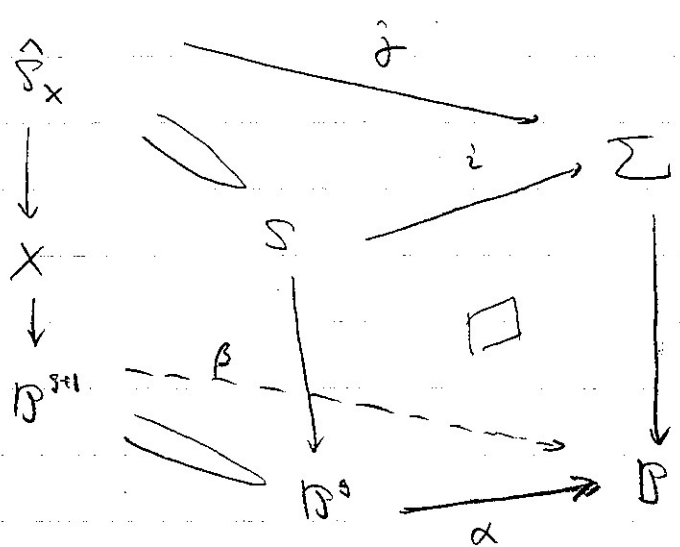
$$\uparrow$$

$$H^0(X, \mathcal{O}(-K_X))$$

Let β be the ~~contravariant~~ projection

$$\beta^* H^0(\mathcal{O}_\Sigma(1)) \longleftarrow \mathbb{P}^{g+1}$$

subset of Σ subset of X



β maps $\hat{S}_X$ into Σ . Hence X into Σ .

It suffices to show

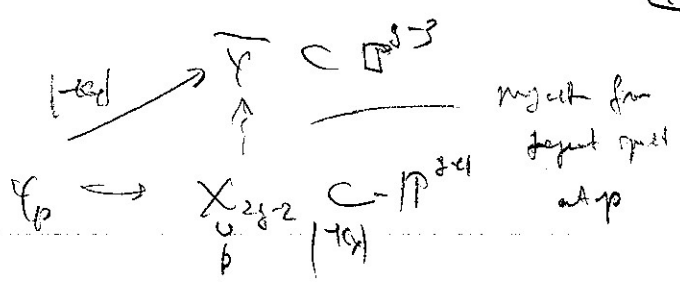
Claim β is embedding. ($\Leftrightarrow j^*$ is injective)

⊙ otherwise β is the composite of the projection off a point $\overset{(P)}{X}$ and α . This implies X is the cone off $\mathbb{R}^n$ over P with vertex p . contradiction. //

By the claim, $X = \Sigma \cap \text{Im } \beta$ complete intersection

then S is so.

§7 Genus bound



Inductive structure of $\{ \text{Gen. Fam. in dim. } n \}$.

Assume $(-K_X)^3 \geq 10$

$X \ni p$ general point

$Y_p = \text{Bl}_p X \quad -K_Y = \pi^*(-K_X) - 2E \quad \left(\begin{array}{l} E \cong \mathbb{P}^2 \\ \mathcal{O}_E(E) = \mathcal{O}(1) \end{array} \right)$

Y_p is not Fam in general, since there ~~exists~~ ^{usually exists} many sec. curves passing through p . But each Fam, $-K_Y$ is

self ad. big. The a.c. add $\overline{Y}_p = \text{Proj} \bigoplus_{n \geq 0} \mathcal{O}(-nK_Y)$

is a Gorenstein $\mathbb{P}^3$ -fold. Gen. drops by 4.

$\mathbb{P}^{2g+1} \supset X \xrightarrow{\quad} \overline{Y}_p \subset \mathbb{P}^{2g+1} \quad \left(\begin{array}{l} \overline{Y}_p \text{ contains a Veronese} \\ \text{surface as the image} \\ \text{of } E \end{array} \right)$
 gen $g \quad \quad \quad \text{gen } g-4.$

If X is decomposable, then so is $\overline{Y}_p$.

Proof of Thm A. It suffices to show the non-existence

for $g = 11, 13, 14$ and 16.

X gen 16 $\Rightarrow \overline{Y}_p$ genus 12 By Thm A, $\overline{Y}_p$ is smooth

Proc $\overline{Y}_p = \mathbb{Z}(-k)$. But $\overline{Y}_p$ cuts $E \cong \mathbb{P}^2$.

contradict

X gen 14 $\Rightarrow \overline{Y}_p$ genus 10 $\overline{Y}_p \subset \Sigma_{16}^5$ by Thm B.

But Σ_{16}^5 does not contain a Veronese surface.

Gorenstein Fano 3-fold

JAMI talk
(John Hopkins U.)

4/13/96 (Sat)

§1 Definition
Ladder

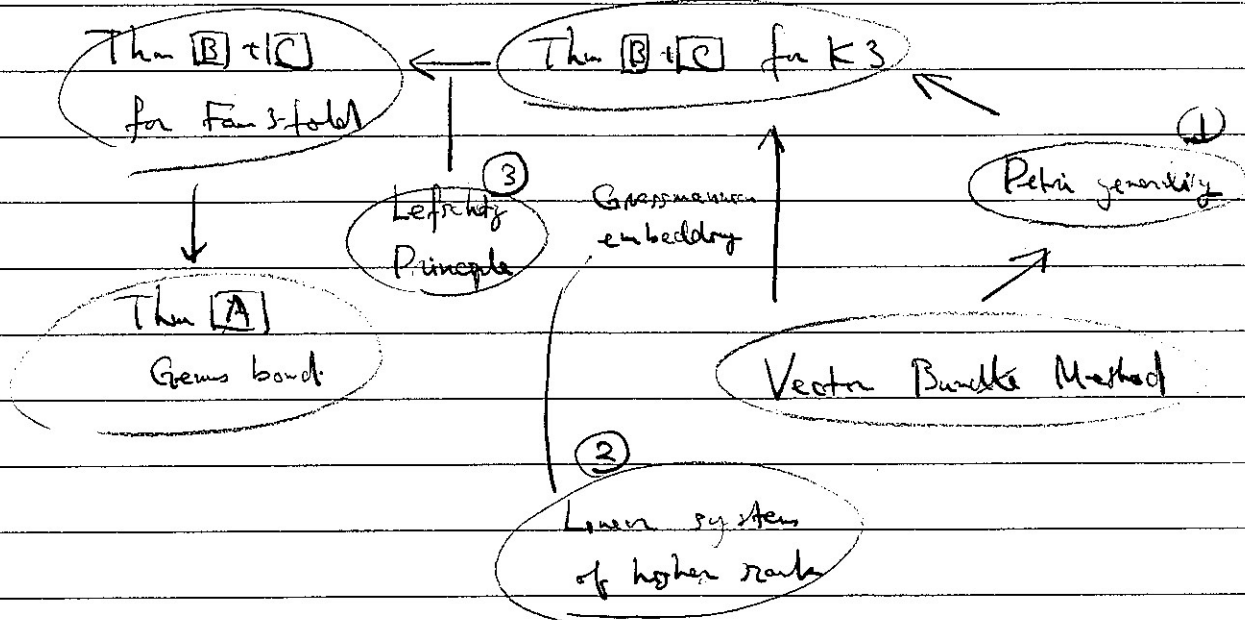
§ goodman $S \in (K_X)$ RDP K_3

$$C \subset S \subset X$$

$$\mathbb{P}^{3+1} \quad \mathbb{P}^3 \quad \mathbb{P}^{3+1}$$

§2 Examples Blc $\mathbb{P}^3$, Homogeneous space of corank 3

§3 Main Theorem $[A] + [B] + [C]$



§4 ① Petri generality indecomposable $\Rightarrow$ Petri gen $\Rightarrow$ num. g. all

§5 ② L.S.T for K_3 $X: \text{f.a.}$ $S: K_3$ C

§6 ③ Lefschetz principle

§7 ④ Gens bound

(K3 as a surface)
J. Wahl 1991 K_3 ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ ⑪ ⑫ ⑬ ⑭ ⑮ ⑯ ⑰ ⑱ ⑲ ⑳ ㉑ ㉒ ㉓ ㉔ ㉕ ㉖ ㉗ ㉘ ㉙ ㉚ ㉛ ㉜ ㉝ ㉞ ㉟ ㊱ ㊲ ㊳ ㊴ ㊵ ㊶ ㊷ ㊸ ㊹ ㊺ ㊻ ㊼ ㊽ ㊾ ㊿ ㏀ ㏁ ㏂ ㏃ ㏄ ㏅ ㏆ ㏇ ㏈ ㏉ ㏊ ㏋ ㏌ ㏍ ㏎ ㏏ ㏐ ㏑ ㏒ ㏓ ㏔ ㏕ ㏖ ㏗ ㏘ ㏙ ㏚ ㏛ ㏜ ㏝ ㏞ ㏟ ㏠ ㏡ ㏢ ㏣ ㏤ ㏥ ㏦ ㏧ ㏨ ㏩ ㏪ ㏫ ㏬ ㏭ ㏮ ㏯ ㏰ ㏱ ㏲ ㏳ ㏴ ㏵ ㏶ ㏷ ㏸ ㏹ ㏺ ㏻ ㏼ ㏽ ㏾ ㏿ 㐀 㐁 㐂 㐃 㐄 㐅 㐆 㐇 㐈 㐉 㐊 㐋 㐌 㐍 㐎 㐏 㐐 㐑 㐒 㐓 㐔 㐕 㐖 㐗 㐘 㐙 㐚 㐛 㐜 㐝 㐞 㐟 㐠 㐡 㐢 㐣 㐤 㐥 㐦 㐧 㐨 㐩 㐪 㐫 㐬 㐭 㐮 㐯 㐰 㐱 㐲 㐳 㐴 㐵 㐶 㐷 㐸 㐹 㐺 㐻 㐼 㐽 㐾 㐿 㑀 㑁 㑂 㑃 㑄 㑅 㑆 㑇 㑈 㑉 㑊 㑋 㑌 㑍 㑎 㑏 㑐 㑑 㑒 㑓 㑔 㑕 㑖 㑗 㑘 㑙 㑚 㑛 㑜 㑝 㑞 㑟 㑠 㑡 㑢 㑣 㑤 㑥 㑦 㑧 㑨 㑩 㑪 㑫 㑬 㑭 㑮 㑯 㑰 㑱 㑲 㑳 㑴 㑵 㑶 㑷 㑸 㑹 㑺 㑻 㑼 㑽 㑾 㑿 㒀 㒁 㒂 㒃 㒄 㒅 㒆 㒇 㒈 㒉 㒊 㒋 㒌 㒍 㒎 㒏 㒐 㒑 㒒 㒓 㒔 㒕 㒖 㒗 㒘 㒙 㒚 㒛 㒜 㒝 㒞 㒟 㒠 㒡 㒢 㒣 㒤 㒥 㒦 㒧 㒨 㒩 㒪 㒫 㒬 㒭 㒮 㒯 㒰 㒱 㒲 㒳 㒴 㒵 㒶 㒷 㒸 㒹 㒺 㒻 㒼 㒽 㒾 㒿 㓀 㓁 㓂 㓃 㓄 㓅 㓆 㓇 㓈 㓉 㓊 㓋 㓌 㓍 㓎 㓏 㓐 㓑 㓒 㓓 㓔 㓕 㓖 㓗 㓘 㓙 㓚 㓛 㓜 㓝 㓞 㓟 㓠 㓡 㓢 㓣 㓤 㓥 㓦 㓧 㓨 㓩 㓪 㓫 㓬 㓭 㓮 㓯 㓰 㓱 㓲 㓳 㓴 㓵 㓶 㓷 㓸 㓹 㓺 㓻 㓼 㓽 㓾 㓿 㔀 㔁 㔂 㔃 㔄 㔅 㔆 㔇 㔈 㔉 㔊 㔋 㔌 㔍 㔎 㔏 㔐 㔑 㔒 㔓 㔔 㔕 㔖 㔗 㔘 㔙 㔚 㔛 㔜 㔝 㔞 㔟 㔠 㔡 㔢 㔣 㔤 㔥 㔦 㔧 㔨 㔩 㔪 㔫 㔬 㔭 㔮 㔯 㔰 㔱 㔲 㔳 㔴 㔵 㔶 㔷 㔸 㔹 㔺 㔻 㔼 㔽 㔾 㔿 㕀 㕁 㕂 㕃 㕄 㕅 㕆 㕇 㕈 㕉 㕊 㕋 㕌 㕍 㕎 㕏 㕐 㕑 㕒 㕓 㕔 㕕 㕖 㕗 㕘 㕙 㕚 㕛 㕜 㕝 㕞 㕟 㕠 㕡 㕢 㕣 㕤 㕥 㕦 㕧 㕨 㕩 㕪 㕫 㕬 㕭 㕮 㕯 㕰 㕱 㕲 㕳 㕴 㕵 㕶 㕷 㕸 㕹 㕺 㕻 㕼 㕽 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