

Birational classification of varieties

James M^cKernan

UCSB

A little category theory

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- It is the aim of higher dimensional geometry to classify algebraic varieties up to birational equivalence.
- Thus the objects are algebraic varieties, but what are the morphisms?

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- Mori theory does **not** say much about finite maps.
- It **does** have a lot to say about morphisms with connected fibres.
- In fact any morphism $f: X \longrightarrow Y$ such that $f_*\mathcal{O}_X = \mathcal{O}_Y$ will be called a **contraction morphism**. If X and Y are normal, this is the same as requiring the fibres of f to be connected.

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- Traditionally the approved way to study a projective variety is to embed it in projective space, and consider the family of hyperplane sections.
- In Mori theory, we focus on **curves**, not **divisors**.
- In fact a contraction morphism $f: X \longrightarrow Y$ is determined by the curves which it contracts. Indeed Y is clearly determined topologically, and the condition $\mathcal{O}_Y = f_*\mathcal{O}_X$ determines the algebraic structure.

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$$\begin{aligned} \text{NE}(X) - \{0\} \quad & \text{by} \\ [C] & \longrightarrow H \cdot C. \end{aligned}$$

- Given f , set $D = f^*H$, where H is an ample divisor on Y . Then D is nef, that is $D \cdot C \geq 0$, for every curve C .

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- Note that if D is semiample, it is certainly nef.

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- In this example, the correspondence between faces and contractions is complete and in fact every nef divisor is semiample.

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- $\text{Aut}(X)$ is large; it contains $\text{SL}(2, \mathbb{Z})$.
- There are many contractions. Start with either of the two projections and act by $\text{Aut}(X)$.

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- $NE(X)$ is one half of the classic circular cone $x^2 + y^2 = z^2 \subset \mathbb{R}^3$. Thus many faces don't correspond to contractions.
- Many nef divisors are not semiample. Indeed, even on an elliptic curve there are numerically trivial divisors which are not torsion.

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- $\delta^2 = 1 - g < 0$; it is contracted by the Abel-Jacobi map. So δ spans a ray. But what is the other ray?
- Conjecturally it spanned by the class of a curve of self-intersection zero. But why could there not be another curve Σ , such that $\Sigma^2 < 0$?

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- Indeed the existence of such a curve would imply that the pullback of S along $\Sigma \longrightarrow C$ splits, which contradicts stability.
- We really need to take the closure, to define $\text{NE}(S)$.

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- What went wrong?

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- Consider the case of curves.

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- So let us now consider surfaces.

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 - K_S is ample. S is of general type. Note that S is forced to be singular in general.
- The problem, as we have already seen, is that we can destroy this picture, simply by blowing up. It is the aim of the MMP to reverse the process of blowing up.

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- Moreover, we can contract R , $\phi_R: X \longrightarrow Y$.

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 - Z is a surface. ϕ blows down a -1 -curve.

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- If $\dim Z = 2$ then replace S with Z , and continue.

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Our aim is to remove this curve or reduce the question to a lower dimensional one.
- By the Cone Theorem, there is an extremal contraction, $\pi: X \longrightarrow Y$, of relative Picard number one such that for a curve C' , $\pi(C')$ is a point iff C' is homologous to C .

Analyzing π

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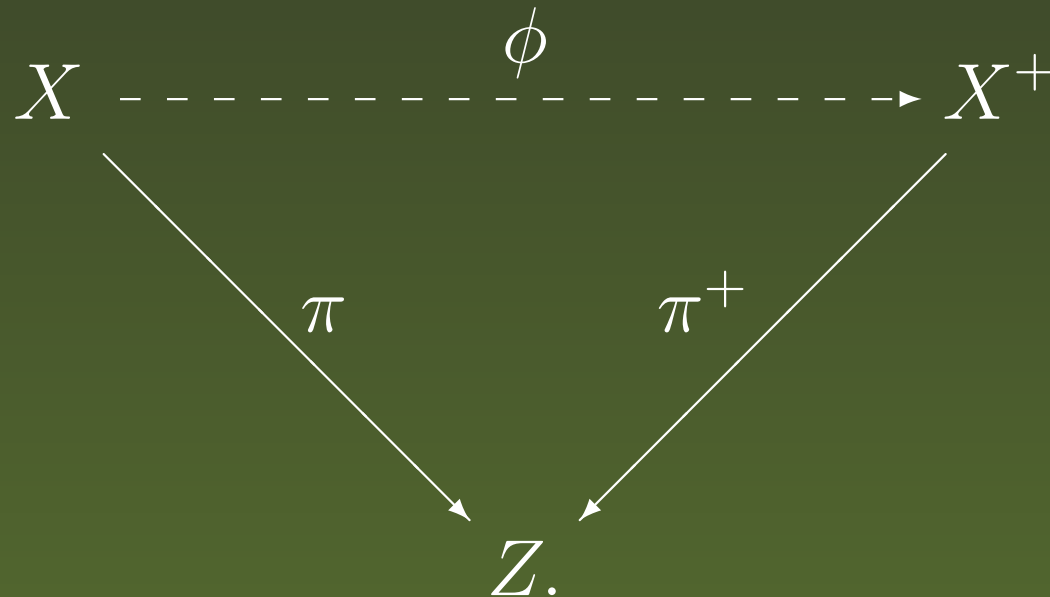
- If the fibres of π have dimension at least one, then we have a Mori fibre space, that is $-K_X$ is π -ample, π has connected fibres and relative Picard number one. We have reduced the question to a lower dimensional one: **STOP**.
- If π is birational and the locus contracted by π is a divisor, then even though Y might be singular, it will at least be \mathbb{Q} -factorial (for every Weil divisor D , some multiple is Cartier).
Replace X by Y and keep going.

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- If the locus contracted by π is not a divisor, that is, π is small, then Y is not \mathbb{Q} -factorial.
- Instead of contracting C , we try to replace X by another birational model X^+ , $X \dashrightarrow X^+$, such that $\pi^+ : X^+ \longrightarrow Y$ is K_{X^+} -ample.



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- Even supposing we can perform a flip, how do we know that this process terminates?
- It is clear that we cannot keep contracting divisors, but why could there not be an infinite sequence of flips?

Adjunction and Vanishing, I

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- Both of these results have far reaching generalisations, whose form dictates the main definitions of the subject.

An illustrative example

- Let S be a smooth projective surface and let $E \subset S$ be a -1 -curve, that is $K_S \cdot E = -1$ and $E^2 = -1$. We want to contract E .

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- Then pick b so that $(K_S + aH + bE) \cdot E = 0$. Note that $b > 0$ (in fact typically b is very large).
- Now we consider the rational map given by $|mD|$, for $m \gg 0$ and sufficiently divisible.

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- So by Kawamata-Viehweg Vanishing

$$H^1(S, \mathcal{O}_S(mD - E)) = H^1(S, \mathcal{O}_S(K_S + G + (m - 1)D)) = 0.$$

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- B is ample, so we have the start of an induction.
- By vanishing, the map

$$H^0(S, \mathcal{O}_S(mD)) \longrightarrow H^0(E, \mathcal{O}_E(mD))$$

is surjective. Thus $|mD|$ is base point free and the resulting map $S \longrightarrow T$ contracts E .

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- Observe that if we set $G' = \pi_* G$, then G' has high multiplicity along p , the image of E (that is b is large).
- In general, we manufacture a divisor E by picking a point $x \in X$ and then pick H with high multiplicity at x .
- Next resolve singularities $\tilde{X} \longrightarrow X$ and restrict to an exceptional divisor E , whose centre has high multiplicity w.r.t H (strictly speaking a log canonical centre of $K_X + H$).

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- We say that the pair (X, Δ) is **klt** if the coefficients of Γ are always less than one.

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- **Moreover** if $K_X + S + B$ is plt then $K_S + D$ is klt.

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- If we take a cover with appropriate ramification, then we can eliminate any component with coefficient less than one.
- (Kawamata-Viehweg vanishing) Suppose that $K_X + \Delta$ is **klt** and L is a line bundle such that $L - (K_X + \Delta)$ is big and nef. Then, for $i > 0$,

$$H^i(X, L) = 0.$$

Summary

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- To achieve this birational classification, we propose to use the MMP.

Two main Conjectures

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To finish the proof of the existence of the MMP, we need to prove the following two conjectures:

Conjecture. (*Existence*) Suppose that $K_X + \Delta$ is kawamata log terminal. Let $\pi: X \longrightarrow Y$ be a small extremal contraction. Then the flip of π exists.

Conjecture. (*Termination*) There is no infinite sequence of kawamata log terminal flips.

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Conjecture. (*Abundance*) Suppose that $K_X + \Delta$ is kawamata log terminal and nef.
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Considering the resulting morphism $\phi: X \longrightarrow Y$, we recover the Kodaira-Enriques classification of surfaces.