Resolution and logarithmic resolution by weighted blowing up

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Work with Michael Tëmkin and Jarosław Włodarczyk
and work by Ming Hao Quek

Also parallel work by M. McQuillan
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Fact

This works for curves but not in general.

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(1) The worst singularity is the origin.

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$x = x'z, \; y = y'z,$ giving
$$x'^2 z^2 - y'^2 z^3 = 0, \quad \text{or} \quad z^2(x'^2 - y'^2 z) = 0.$$

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$x'^2 z^2 - y'^2 z^3 = 0, \quad \text{or} \quad z^2(x'^2 - y'^2 z) = 0.$
The first term is exceptional, the second is the same as X.

Two theorems

Nevertheless:

Theorem (ℵ-T-W, McQuillan, 2019, characteristic 0)

There is a functor F associating to a singular subvariety $X \subset Y$ of a smooth variety Y, a center $\bar{J}$ with stack theoretic weighted blowing up $Y' \to Y$ and proper transform $(X' \subset Y') = F(X \subset Y)$ such that $\operatorname{maxinv}(X') < \operatorname{maxinv}(X)$. In particular, for some n the iterate $(X_n \subset Y_n) := F^{\circ n}(X \subset Y)$ of F has X_n smooth.

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Theorem (Quek, 2020, characteristic 0)

There is a functor F associating to a logarithmically singular subvariety $X \subset Y$ of a logarithmically smooth variety Y, a logarithmic center $\bar{J}$ with stack theoretic logarithmic blowing up $Y' \to Y$ and proper transform $(X' \subset Y') = F(X \subset Y)$ such that $\operatorname{maxloginv}(X') < \operatorname{maxloginv}(X)$. In particular, for some n the iterate $(X_n \subset Y_n) := F^{\circ n}(X \subset Y)$ of F has X_n logarithmically smooth.

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Hironaka's theorem resolves varieties. What can you do with families of varieties $X \to B$?

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- A toroidal morphism $X \to B$ of toroidal embeddings is étale locally isomorphic to a toric morphism.

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- toric blowups

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Theorem (ℵ-T-W 2020)

Given $X \to B$ there is a relatively functorial logarithmically smooth modification $X' \to B'$.

- This respects $\mathrm{Aut}_B X$.
- Does not modify log smooth fibers.

Context: principalization

- Following Hironaka, the above theorem is based on embedded methods:

Theorem (ℵ-T-W 2020)

Given $Y \to B$ logarithmically smooth and $\mathcal{I} \subset \mathcal{O}_Y$, there is a relatively functorial logarithmically smooth modification $Y' \to B'$ such that $\mathcal{I}\mathcal{O}_{Y'}$ is monomial.

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- This is done by a sequence of logarithmic modifications,
- where in each step E becomes part of the divisor $D_{Y'}$.

Example 1

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- Blow up $J = (x,u)$
- $\mathcal{I}\mathcal{O}_{Y'} = \mathcal{O}(-2E)$

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- By functoriality blow up J_0 so that $f^*J_0 = J = (x, u)$.
- Blow up $J_0 = (x, \sqrt{v})$
- Whatever J_0 is, the blowup is a stack.

Example 1/2: charts

- x chart: $v = v'x^2$:

$$(x^2, v) = (x^2, v'x^2) = (x^2)$$

exceptional, so monomial.

- $\sqrt{v}$ chart: $v = w^2, x = x'w$, with ± 1 action $(x', w) \mapsto (-x', -w)$:

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- The schematic quotient of the above is not toroidal.

Resolution again

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Example

For $X = V(x^2 - y^2 z)$ we have $inv_p(X) = (2, 3, 3)$
We read it from the degrees of terms.
The center is:
$J = (x^2, y^3, z^3)$; $\bar{J} = (x^{1/3}, y^{1/2}, z^{1/2})$.

Example: blowing up Whitney's umbrella $x^2 = y^2 z$

The blowing up $Y' \to Y$ makes $\bar{J} = (x^{1/3}, y^{1/2}, z^{1/2})$ principal. Explicitly:

- The z chart has $x = w^3 x_3, y = w^2 y_3, z = w^2$ with chart

$$Y' \;=\; [\,\mathrm{Spec}\,\mathbb{C}[x_3, y_3, w] \;/\; (\pm 1)\,],$$

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  $$w^6(x_3^2 - y_3^2),$$

  and the invariant of the proper transform $(x_3^2 - y_3^2)$ is $(2, 2) < (2, 3, 3)$.

Order (following Kollár's book)

We fix Y smooth and $\mathcal{I} \subset \mathcal{O}_Y$.

Definition

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- The invariant starts with $a_1 = \operatorname{ord}_p(\mathcal{I})$.

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Proposition

The order is upper semicontinuous.

Proof.

$V(\mathcal{D}^{a-1}\mathcal{I}) = \{p : \mathrm{ord}_p(\mathcal{I}) \geq a\}$. ♠

Maximal contact (following Kollár's book)

Definition

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Lemma (Hironaka,Giraud)

In characteristic 0 a maximal contact exists on an open neighborhood of p.

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Example

For $\mathcal{I} = (x^2 - y^2 z)$ we have $\mathrm{ord}_p \mathcal{I} = 2$ with $x_1 = x$
(or αx+h.o.t. in $\mathcal{D}(\mathcal{I})$).

Coefficient ideals (treated following Kollár)

We must restrict to $x_1 = 0$ the data of all

$$\mathcal{I},\ \mathcal{D}\mathcal{I},\ \ldots,\ \mathcal{D}^{a_1-1}\mathcal{I}$$

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We combine these in

$$C(\mathcal{I}, a_1)\ :=\ \sum f\left(\mathcal{I}, \mathcal{D}\mathcal{I}, \ldots, \mathcal{D}^{a_1-1}\mathcal{I}\right),$$

where f runs over monomials $f = t_0^{b_0} \cdots t_{a_1-1}^{b_{a_1-1}}$ with weights

$$\sum b_i(a_1 - i) \geq a_1!.$$

Define $\mathcal{I}[2] = C(\mathcal{I}, a_1)|_{x_1=0}$.

Defining $J_{\mathcal{I}}$

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$$\text{inv}_p(\mathcal{I}) = (a_1, \ldots, a_k) := \left(a_1, \frac{\text{inv}_p(\mathcal{I}[2])}{(a_1 - 1)!}\right)$$

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Write $(a_1, \ldots, a_k) = \ell(1/w_1, \ldots, 1/w_k)$ with $w_i, \ell \in \mathbb{N}$ and $\gcd(w_1, \ldots, w_k) = 1$. We set

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Examples of $J_{\mathcal{I}}$

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(1) for $X = V(x^5 + x^3 y^3 + y^8)$ we have $\mathcal{I}[2] = (y)^{180}$, so
$J_{\mathcal{I}} = (x^5, y^{180/24}) = (x^5, y^{15/2})$, $\bar{J}_{\mathcal{I}} = (x^{1/3}, y^{1/2})$.

(2) for $X = V(x^5 + x^3 y^3 + y^7)$

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(2) for $X = V(x^5 + x^3 y^3 + y^7)$ we have $\mathcal{I}[2] = (y)^{7 \cdot 24}$, so $J_{\mathcal{I}} = (x^5, y^7)$, $\bar{J}_{\mathcal{I}} = (x^{1/7}, y^{1/5})$.

Implementation: Jonghyun Lee, Anne Frühbis-Krüger.

Properties of the invariant

Proposition

- inv_p *is well-defined.*
- inv_p *is lexicographically upper-semi-continuous.*
- inv_p *is functorial.*
- inv_p *takes values in a well-ordered set.*

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Theorem (MC-invariance [Włodarczyk, Kollár])

Given maximal contacts x_1, x_1' *there are étale* $\pi, \pi' : \tilde{Y} \rightrightarrows Y$ *such that* $\pi^* x_1 = \pi'^* x_1' \ldots$ *and* $\pi^* C(\mathcal{I}, a_1) = \pi'^* C(\mathcal{I}, a_1)$.

Definition of $Y' \to Y$

Let $\bar{J} = (x_1^{1/w_1}, \ldots, x_k^{1/w_k})$. Define the graded algebra

$$\mathcal{A}_{\bar{J}} \quad \subset \quad \mathcal{O}_Y[T]$$

as the integral closure of the image of

$$\begin{array}{ccc} \mathcal{O}_Y[Y_1, \ldots, Y_n] & \longrightarrow & \mathcal{O}_Y[T] \\ Y_i & \longmapsto & x_i T^{w_i}. \end{array}$$

Definition of $Y' \to Y$

Let $\bar{J} = (x_1^{1/w_1}, \ldots, x_k^{1/w_k})$. Define the graded algebra

$$\mathcal{A}_{\bar{J}} \quad \subset \quad \mathcal{O}_Y[T]$$

as the integral closure of the image of

$$\begin{array}{ccc} \mathcal{O}_Y[Y_1, \ldots, Y_n] & \longrightarrow & \mathcal{O}_Y[T] \\ Y_i & \longmapsto & x_i T^{w_i}. \end{array}$$

Let

$$S_0 \subset \operatorname{Spec}_Y \mathcal{A}_{\bar{J}}, \quad S_0 = V((\mathcal{A}_{\bar{J}})_{>0}).$$

Then

$$Bl_{\bar{J}}(Y) \;:=\; \mathcal{P}roj_Y \mathcal{A}_{\bar{J}} \;:=\; \left[(\operatorname{Spec} \mathcal{A}_{\bar{J}} \smallsetminus S_0) \;/\; \mathbb{G}_m\right].$$

Description of $Y' \to Y$

- **Charts:** The x_1-chart is

$$[\operatorname{Spec} k[u, x_2', \ldots, x_n'] \ / \ \boldsymbol{\mu}_{w_1}],$$

with $x_1 = u^{w_1}$ and $x_i = u^{w_i} x_i'$ for $2 \leq i \leq k$, and induced action:

$$(u, x_2', \ldots, x_n') \ \mapsto \ (\zeta u \, , \, \zeta^{-w_2} x_2' \, , \, \ldots \, , \, \zeta^{-w_k} x_k', \ x_{k+1}', \ldots, x_n').$$

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- **Toric stack:** Consider $\operatorname{Spec} k[x_1, \dots, x_n, T]$ with $\mathbb{G}_m$ action with weights $(w_1, \dots, w_n, -1)$. Let U be the open set where one of the x_i is a unit. Then $Y' = [U/\mathbb{G}_m]$.
  It is an example of a *fantastack* [Geraschenko-Satriano], the stack quotient of a Cox construction.

What is J?

Definition

Consider the Zariski-Riemann space $\mathbf{ZR}(Y)$ with its sheaf of ordered groups Γ, and associated sheaf of rational ordered group $\Gamma \otimes \mathbb{Q}$.

- A valuative $\mathbb{Q}$-ideal is

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A center is in particular a valuative $\mathbb{Q}$-ideal. It is also an idealistic exponent or graded sequence of ideals.

Admissibility and coefficient ideals

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This is equivalent to $\mathcal{I}\mathcal{O}_{Y'} = E^\ell \mathcal{I}'$, *with* $J = \bar{J}^\ell$ *and* $\mathcal{I}'$ *an ideal.*

Indeed, on Y' the center J becomes E^ℓ, in particular principal.
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Proposition

A center J *is* $\mathcal{I}$*-admissible if and only if* $J^{(a_1-1)!}$ *is* $C(\mathcal{I}, a_1)$*-admissible.*

The key theorems

Theorem

$\mathrm{inv}_p(\mathcal{I})$ *is the maximal invariant of an* $\mathcal{I}$*-admissible center.*

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This is a consequence of Kollár's $\mathcal{D}$-balanced property of $C(\mathcal{I}, a_1)$.

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- This reduces logarithmic invariants respecting logarithmic, hence exceptional, divisors.

The end

Thank you for your attention