On semi-invariants of filtered representations of quivers and the cotangent bundle of the enhanced Grothendieck-Springer resolution

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Table of contents

Standing assumption: work over $\mathbb{C}$. Definitions:

A *quiver* Q is a directed graph. Assume Q to be finite, i.e., Q has finite number $\{1, 2, \ldots, Q_0\}$ of vertices and finite number $\{a_1, \ldots, a_{Q_1}\}$ of arrows which come equipped with two functions: for each arrow $\overset{i}{\bullet} \xrightarrow{a} \overset{j}{\bullet}$, $t, h : Q_1 \to Q_0$ map $t(a) = i$ and $h(a) = j$.

A *representation* of a quiver assigns a finite-dimensional vector space to each vertex and a linear map to each arrow.

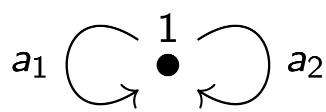
A *dimension vector* of Q is an element of the form $\beta \in \mathbb{Z}_{\geq 0}^{Q_0}$.

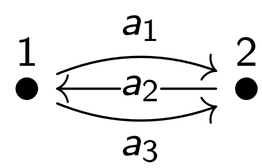
Given Q and β, the *representation space* is

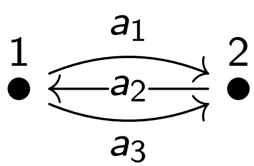
$$Rep(Q, \beta) := \prod_{a \in Q_1} \mathrm{Hom}(\mathbb{C}^{\beta_{t(a)}}, \mathbb{C}^{\beta_{h(a)}}).$$

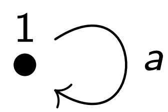
$Rep(Q, \beta)$ has a natural $\mathbb{G}_\beta$-action, where $\mathbb{G}_\beta := \prod_{i \in Q_0} GL_{\beta_i}$.

Background. Examples:

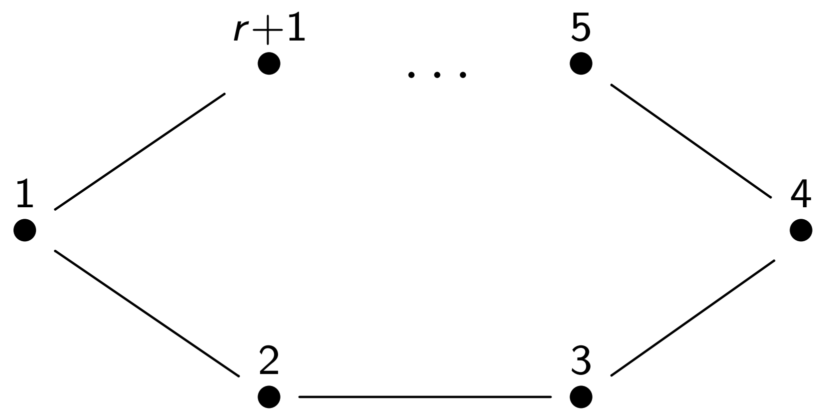
- 2-Jordan 

, 3-Kronecker 

,
- Cycle 

, loop 

,
- ADE-Dynkin if the underlying graph is of ADE-Dynkin type,
- Affine (type) $\widetilde{A}_r$-Dynkin



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Relations of quiver representations to classical linear algebra: the study of GL_n-orbits on $\mathfrak{gl}_n = \mathrm{Lie}(GL_n)$.

Filtered quiver representations. Definitions:

Assume Q and β as before. Let

$$F_i^\bullet : \{0\} = U_i^0 \subseteq U_i^1 \subseteq U_i^2 \subseteq \ldots \subseteq U_i^N = \mathbb{C}^{\beta_i}$$

be a sequence of vector spaces, one for each $i \in Q_0$.
Then $F^\bullet Rep(Q, \beta)$ is a subspace of $Rep(Q, \beta)$ whose linear maps preserve the filtration of vector spaces at every level.
$F^\bullet Rep(Q, \beta)$ is called a *filtered quiver variety*.

Let $P_i \subseteq GL_{\beta_i}$ be the largest subgroup preserving the filtration of vector spaces at vertex i. Then $\mathbb{P}_\beta := \prod_{i \in Q_0} P_i$ acts on $F^\bullet Rep(Q, \beta)$ as a change-of-basis.

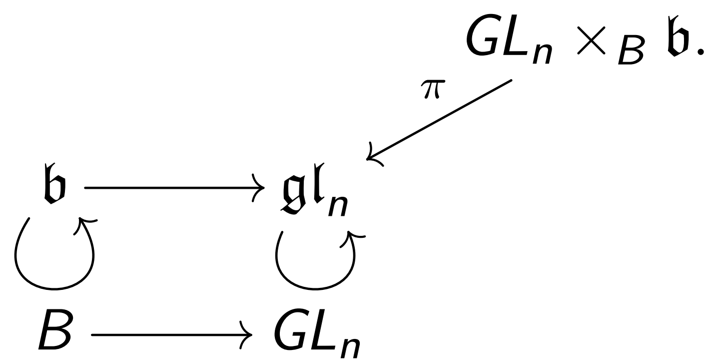
Filtered quiver representations. Examples:

- Q: $\bullet \circlearrowleft$, $\beta = n$, $F^{\bullet}$ is the complete standard filtration of vector spaces. Then $F^{\bullet}Rep(Q, \beta) = \mathfrak{b}_n$, the space of $n \times n$ upper triangular matrices, with B-conjugation action on $\mathfrak{b}_n$, where $\mathrm{Lie}(B) = \mathfrak{b}_n$.
- Q: $\bullet \longrightarrow \bullet$, $\beta = (n, n)$, $F^{\bullet}$ is the complete standard filtration of vector spaces at each vertex. Then $F^{\bullet}Rep(Q, \beta) = \mathfrak{b}_n$ and $B_n \times B_n \subseteq GL_n(\mathbb{C}) \times GL_n(\mathbb{C})$ acts on the filtered representation space via the left-right action.

Relations to classical (19^{th} century) linear algebra: the study of B-orbits on $\mathfrak{b} = \mathrm{Lie}(B)$.

Grothendieck-Springer resolution.

There are embeddings $B \overset{\psi}{\hookrightarrow} GL_n$ and $\mathfrak{b} \overset{\varphi}{\hookrightarrow} \mathfrak{gl}_n$ such that φ is ψ-equivariant. Consider



Lemma

Given $\widetilde{\mathfrak{gl}_n} := \{(x, \mathfrak{b}) \in \mathfrak{gl}_n \times GL_n/B : x \in \mathfrak{b}\}$, $\widetilde{\mathfrak{gl}_n} \cong GL_n \times_B \mathfrak{b}$.

Proof.

There is a map $(GL_n \times \mathfrak{b})/B \to \widetilde{\mathfrak{gl}_n}$, where $(g, x) \mapsto (gxg^{-1}, (g.B)/B)$. This map is GL_n-equivariant and is an isomorphism. □

Grothendieck-Springer resolution.

Since GL_n acts on $\widetilde{\mathfrak{gl}_n}$ via $g.(x, \mathfrak{b}) = (xg^{-1}, g\mathfrak{b}g^{-1})$ and on $\mathfrak{gl}_n$ via the adjoint action, $\widetilde{\mathfrak{gl}_n} \to \mathfrak{gl}_n$ is a GL_n-equivariant map.

Lemma

There is a bijection between GL_n-orbits on $\widetilde{\mathfrak{gl}_n}$ and B-orbits on $\mathfrak{b}$.

Proof.

Consider $(GL_n \times \mathfrak{b})/B \to \mathfrak{b}/B$, where $(g, x) \mapsto gxg^{-1}$. This map is well-defined up to the B-conjugation action. Since the map is GL_n-equivariant, it descends to an isomorphism $\widetilde{\mathfrak{gl}_n}/GL_n \cong \mathfrak{b}/B$ as orbit spaces. □

Moral of the story: study the B-action on $\mathfrak{b}$.

Furthermore, $\mathbb{P}_\beta$-action on $F^\bullet Rep(Q, \beta)$ generalizes B-action on $\mathfrak{b}$ (21^{st} century).

Comparing $\mathbb{U}_\beta$-invariants and $\mathbb{P}_\beta$-semi-invariants, where $\mathbb{U}_\beta$ is the maximal unipotent subgroup of $\mathbb{P}_\beta$.

Definition: $f \in \mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{P}_\beta}$ is an *invariant polynomial* if $f(g.x) = f(x)$ for all $g \in \mathbb{P}_\beta$ and $x \in F^\bullet Rep(Q,\beta)$.

Definition: $f \in \mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{P}_\beta,\chi}$ is a *semi-invariant polynomial* if $f(g.x) = \chi(g)f(x)$ for all $g \in \mathbb{P}_\beta$ and $x \in F^\bullet Rep(Q,\beta)$, where $\chi : \mathbb{P}_\beta \to \mathbb{C}^*$ is an algebraic group homomorphism, $\mathbb{C}^* = \mathbb{C} \setminus \{0\}$.

The ring of semi-invariant polynomials is $\bigoplus_\chi \mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{P}_\beta,\chi}$.

Semi-invariants under the $\mathbb{P}_\beta$-action are invariant for $\mathbb{U}_\beta$-action and $\mathbb{U}_\beta$-invariant polynomials that are homogeneous with respect to a generalized Q_0-grading are also semi-invariant (for some χ) for the $\mathbb{P}_\beta$-action. Thus, $\bigoplus_\chi \mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{P}_\beta,\chi} \cong \mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{U}_\beta}$.

$\mathbb{U}_\beta$-invariants and $\mathbb{P}_\beta$-semi-invariants: why are they interesting?

Use invariant and semi-invariant polynomials to construct new and interesting varieties; that is,

- construct the *affine quotient*

$$F^\bullet Rep(Q,\beta)/\!\!/\mathbb{P}_\beta := \mathrm{Spec}(\mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{P}_\beta})$$

  of the vector space $F^\bullet Rep(Q,\beta)$ by $\mathbb{P}_\beta$,

- construct the *geometric (GIT) quotient*

$$F^\bullet Rep(Q,\beta)/\!\!/_\chi\mathbb{P}_\beta := \mathrm{Proj}(\bigoplus_{i\geq 0}\mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{P}_\beta,\chi^i})$$

  of the space $F^\bullet Rep(Q,\beta)$ by $\mathbb{P}_\beta$ twisted by χ.

Filtered quiver varieties of finite *ADE*-Dynkin type.

Basic assumption: let $F^\bullet$ be the complete standard filtration of vector spaces at each vertex. Let $\mathfrak{t}_n \subseteq \mathfrak{gl}_n$ be the set of complex diagonal matrices.

Theorem (Im)

If Q is an ADE-Dynkin quiver and $\beta = (n, \ldots, n) \in \mathbb{Z}_{\geq 0}^{Q_0}$, then $\mathbb{C}[F^\bullet Rep(Q, \beta)]^{\mathbb{U}_\beta} \cong \mathbb{C}[\mathfrak{t}_n^{\oplus Q_1}]$.

Sketch of proof:

- It is clear that $\mathbb{C}[\mathfrak{t}_n^{\oplus r-1}] \subseteq \mathbb{C}[\mathfrak{b}_n^{\oplus r-1}]^{\mathbb{U}_\beta}$.
- Consider the equioriented finite A_r-quiver:

$$\overset{1}{\bullet} \xrightarrow{a_1} \overset{2}{\bullet} \xrightarrow{a_2} \ldots \quad \overset{r-2}{\bullet} \xrightarrow{a_{r-2}} \overset{r-1}{\bullet} \xrightarrow{a_{r-1}} \overset{r}{\bullet} .$$

- Let $A_\alpha = ({}_{(\alpha)}a_{st})$ be a general representation of a_α.

Filtered quiver varieties of finite ADE-Dynkin type.

- Fix a total ordering $\leq$ on pairs (i, j), where $1 \leq i \leq j \leq n$, by defining $(i, j) \leq (i', j')$ if either
  - $i < i'$ or
  - $i = i'$ and $j > j'$.
- For each (i, j), we can write $f \in \mathbb{C}[\mathfrak{b}_n^{\oplus r-1}]^{\mathbb{U}_\beta}$ as

$$f = \sum_K a_{ij}^K f_{ij,K}, \text{ where } f_{ij,K} \in \mathbb{C}[\{{}_{(\alpha)}a_{st} : (s,t) \neq (i,j)\}],$$

  where $a_{ij}^K := \prod_{\alpha=1}^{r-1} {}_{(\alpha)}a_{ij}^{k_\alpha}$.
- Fix the least pair (under $\leq$) (i, j) with $i < j$ for which there exists $K \neq (0, \ldots, 0)$ with $f_{ij,K} \neq 0$; we will continue to denote it by (i, j). If such least pair does not exist, we're done.

Filtered quiver varieties of finite *ADE*-Dynkin type.

- Let $K = (k_1, \ldots, k_{r-1})$. Let $m \geq 1$ be the least integer satisfying the following: for all $p < m$, if some component k_p in K is strictly greater than 0, then $f_{ij,K} = 0$.
- Let U_{ij} be the subgroup of matrices of the form $u_{ij} := (\mathrm{I}_n, \ldots, \mathrm{I}_n, \widehat{u}_m, \mathrm{I}_n, \ldots, \mathrm{I}_n)$, where I_n is the $n \times n$ identity matrix and $\widehat{u}_m$ is the matrix with 1 along the diagonal, the variable u in the (i,j)-entry, and 0 elsewhere.
- $$u_{ij} \cdot {}_{(\alpha)}a_{st} = \begin{cases} {}_{(m)}a_{ij} + {}_{(m)}a_{ii}u & \text{if } \alpha = m \text{ and } (s,t) = (i,j), \\ {}_{(\alpha)}a_{st} & \text{if } s > i \text{ or } s = i \text{ and } t < j. \end{cases}$$

Filtered quiver varieties of finite *ADE*-Dynkin type.

- Now write
$$f = \sum_{k\geq 0} {}_{(m)}a_{ij}^{k} F_k,$$
where $F_k \in \mathbb{C}[\{{}_{(\alpha)}a_{st} : (s,t) \geq (i,j) \text{ and if } (s,t) = (i,j), \text{ then } \alpha > m\}] =: R_0$.
- We have
$$0 = u_{ij}.f - f = \sum_{k\geq 1} \sum_{1\leq l\leq k} {}_{(m)}a_{ij}^{k-l}\, {}_{(m)}a_{ii}^{l} u^{l} \binom{k}{l} F_k.$$
- $\{{}_{(m)}a_{ij}^{k-l} u^{l} : 1 \leq l \leq k, k \geq 0\}$ is linearly independent over R_0.
- Contradiction!

If Q is an ADE-Dynkin quiver, then all classical semi-invariant techniques are applicable!

Classical techniques (for reductive groups) given by

- Schofield-van den Bergh (1999)
- Derksen-Weyman (2000)
- Domokos-Zubkov (2001)

are applicable. For more details, see Appendix of the slides.

Pathways. Definitions:

A *nontrivial path* is a sequence $a_m \cdots a_1$ of arrows such that $t(a_{i+1}) = h(a_i)$ for all $1 \leq i < m$. We write e_i as the *trivial (empty) path* at vertex i.

The *path algebra* $\mathbb{C}Q$ of Q is the $\mathbb{C}$-algebra with basis the paths in Q, with the product of two paths p and q given by $p \circ q = pq$ if $t(p) = h(q)$; otherwise, $p \circ q = 0$.

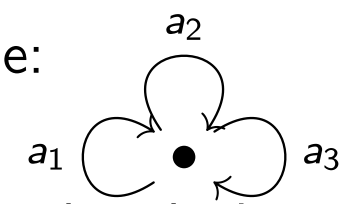
A *relation* of a quiver Q is a subspace of $\mathbb{C}Q$ spanned by linear combinations of paths having a common source and a common target, and of length at least 2 (Michel Brion).

A *quiver with relations* is a pair (Q, I), where Q is a quiver and I is a two-sided ideal of $\mathbb{C}Q$ generated by relations.

The *quotient algebra* $\mathbb{C}Q/I$ is the path algebra of (Q, I).

Pathways.

Example:

Let Q: 

. Then $\mathbb{C}Q = \mathbb{C}\langle a_1, a_2, a_3 \rangle$.
Let I be the ideal generated by $a_i a_j - a_j a_i$, $1 \leq i < j \leq 3$.
Then $\mathbb{C}Q/I = \mathbb{C}[a_1, a_2, a_3]$.

Definition: a path p is *reduced* if it is the class $[p] \neq 0$ in $\mathbb{C}Q/\langle q^2 : q \in \mathbb{C}Q, l(q) \geq 1 \rangle$, where $l(q)$ is the number of arrows in q.

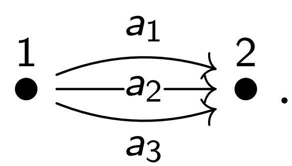
Definition: a *pathway* from vertex i to vertex j is a reduced path from i to j. We define *pathways* of a quiver Q to be the set of all pathways from vertex i to vertex j, where $i, j \in Q_0$.

More examples on the next slide.

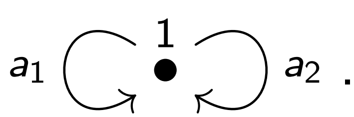
Pathways. Examples:

- Q: 

  Paths of Q consist of $e_1, a, a^2, a^3, \ldots$.
  Pathways of Q consist of e_1 and a.
  This quiver has at most 2 pathways.

- Q: 

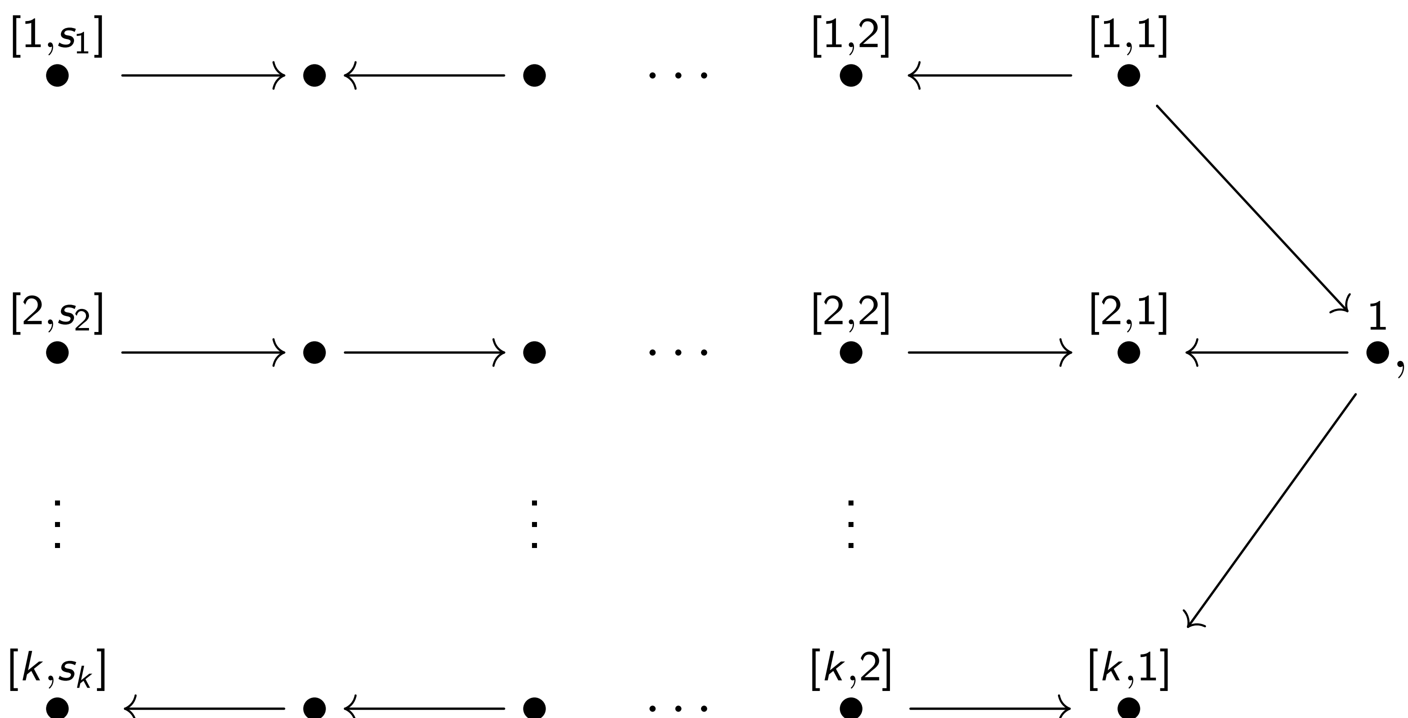
  There is one pathway from vertex 1 to vertex 1: e_1.
  There are 3 pathways from vertex 1 to vertex 2: a_1, a_2, a_3.
  There is one pathway from vertex 2 to vertex 2: e_2.
  This quiver has at most 3 pathways between any two vertices.

- Q: 

  Pathways consist of $e_1, a_1, a_2, a_1a_2, a_2a_1, a_1a_2a_1, a_2a_1a_2$.
  This Q has more than 2 pathways.

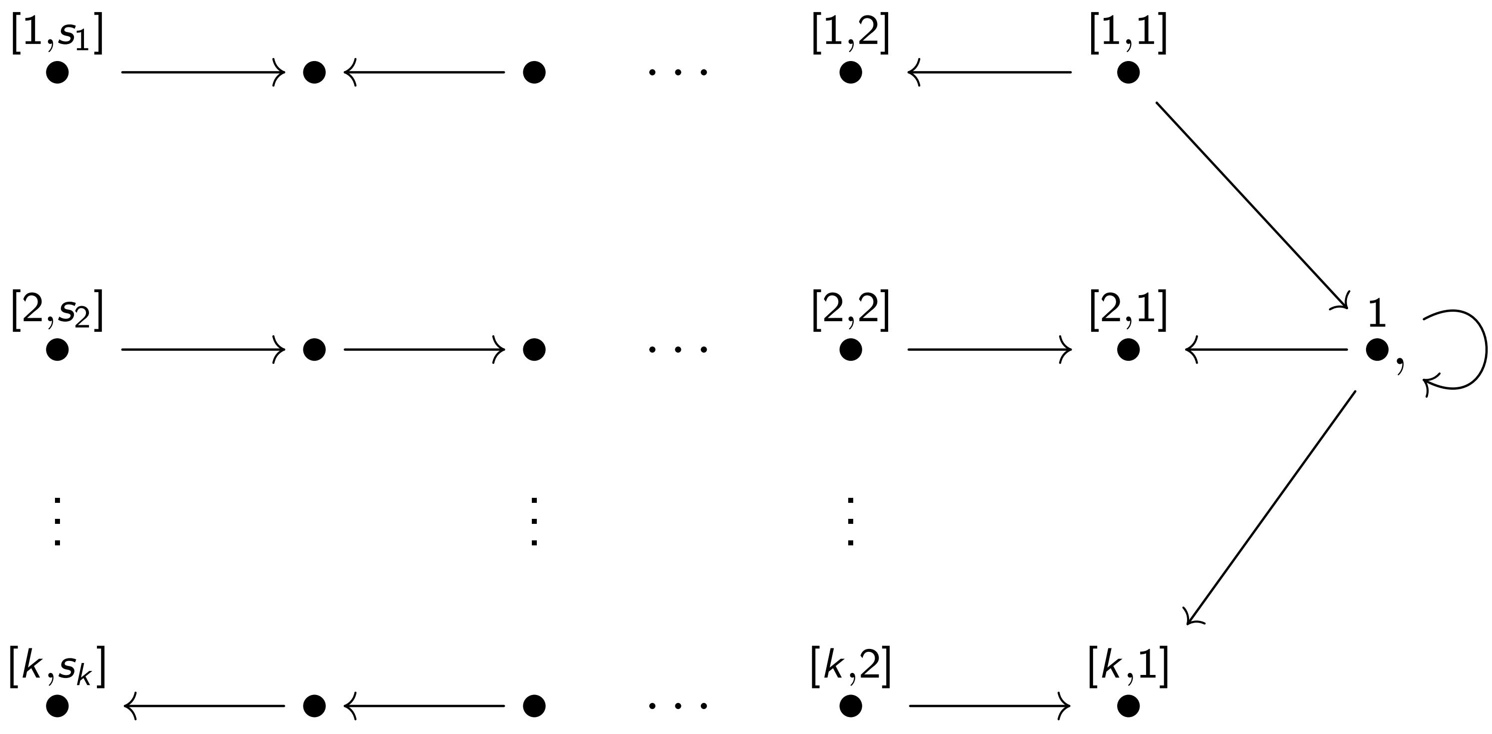
Examples of quivers with at most two pathways between any two vertices.

- *ADE*-Dynkin quivers,
- Framed $\widetilde{A}_r$-Dynkin quivers, which includes $\circ \longrightarrow \bullet \circlearrowleft$,
- Star-shaped quivers have k legs (each of length s_k), e.g.,



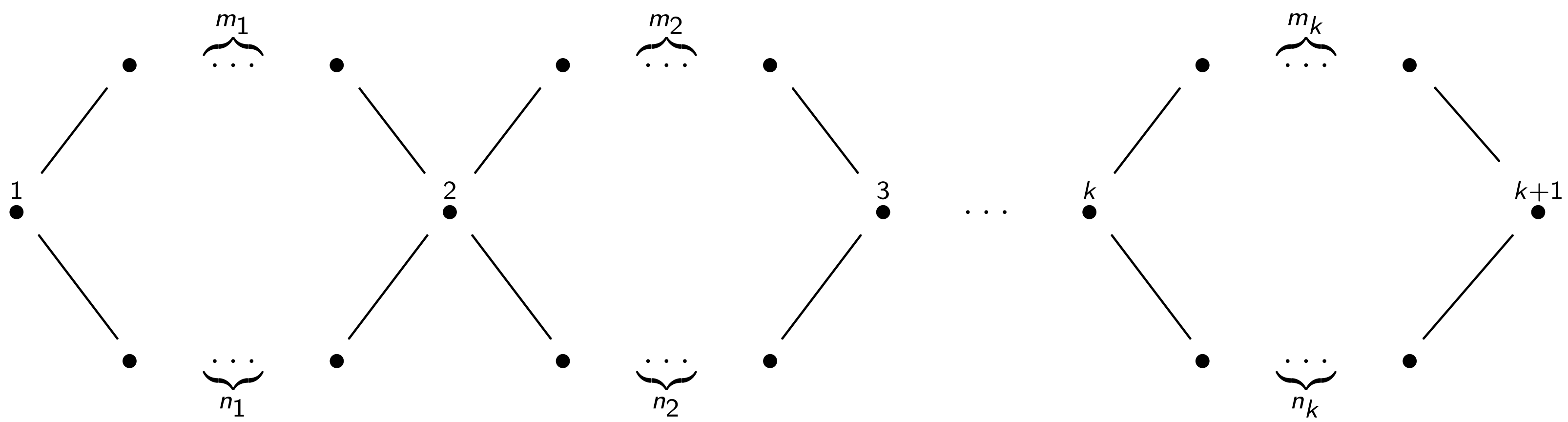
Examples of quivers with at most two pathways.

- Comet-shaped quivers have k legs (each of length s_k), with 1 loop on the central vertex, e.g.,



Examples of quivers with at most two pathways.

- A quiver whose underlying graph is



with the condition that vertices $2, 3, \ldots, k$ are a source or a sink (in any order).

Quivers with at most two pathways.

Basic assumption: let $F^\bullet$ be the complete standard filtration of vector spaces at each nonframed vertex. Let $\mathfrak{t}_n \subseteq \mathfrak{gl}_n$ be the set of complex diagonal matrices, and let $\mathbb{U}_\beta := U^{Q_0} \subseteq B^{Q_0}$, $B \subseteq GL_n(\mathbb{C})$ is subgroup of invertible upper triangular matrices.

Theorem (Im)

Let Q be a quiver and let $\beta = (n, \ldots, n)$. Then Q is a nonframed quiver with at most two distinct pathways between any two vertices if and only if $\mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{U}_\beta} \cong \mathbb{C}[\mathfrak{t}^{\oplus Q_1}]$, where Q_1 is the set of arrows whose tail and head are nonframed vertices.

Remark: want to use classical techniques to obtain semi-invariants for certain filtered quiver representations? Then restrict to quivers with at most 2 pathways between any two of its vertices.

Quivers with at most two pathways.

Theorem (Im)

Let Q be a quiver and let $\beta = (n, \ldots, n)$. Then Q is a nonframed quiver with at most two distinct pathways between any two vertices if and only if $\mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{U}_\beta} \cong \mathbb{C}[\mathfrak{t}^{\oplus Q_1}]$, where Q_1 is the set of arrows whose tail and head are nonframed vertices.

That is, suppose Q is a nonframed quiver. Then

Q has at most two distinct pathways between any two vertices if and only if $\mathbb{C}[F^\bullet Rep(Q,\beta)]^{\mathbb{U}_\beta} \cong \mathbb{C}[\mathfrak{t}^{\oplus Q_1}]$, where Q_1 is the number of arrows of Q.

Sketch of proof: similar to the proof for filtered quiver varieties for finite ADE-Dynkin type.

The end (unless there is more time).

Thank you. Questions?

Construction of $T^*(\mathfrak{b} \times \mathbb{C}^n)$, cf. Nevins' manuscript.

Consider B-action on $\mathfrak{b} \times \mathbb{C}^n$ via $b.(r, i) = (brb^{-1}, bi)$ and $G \times B$-action on $G \times \mathfrak{b} \times \mathbb{C}^n$ via

$$g.(g', r, i) = (g'g^{-1}, r, gi) \text{ and } b.(g', r, i) = (g'b^{-1}, brb^{-1}, i),$$
$$\text{where } b \in B \text{ and } g \in G.$$

This gives two moment maps

$$T^*(\mathfrak{b} \times \mathbb{C}^n) \xrightarrow{\mu_B} \mathfrak{b}^* \cong \mathfrak{gl}_n/\mathfrak{u}^+,\ (r, s, i, j) \mapsto [r, s] + ij, \text{ and}$$
$$T^*(G \times \mathfrak{b} \times \mathbb{C}^n) \xrightarrow{\mu_{G\times B}} \mathfrak{g}^* \times \mathfrak{b}^*,\ (g', \theta, r, s, i, j) \mapsto (\theta - ij, [r, s] + \overline{\theta}),$$
$$\text{where } \overline{\theta} : \mathfrak{gl}_n \to \mathfrak{b}^*.$$

There is a bijection of B-orbits on $\mu_B^{-1}(0)$ and $G \times B$-orbits on $\mu_{G\times B}^{-1}(0)$:

$$\mu_B^{-1}(0)/B \cong \mu_{G\times B}^{-1}(0)/G \times B \cong T^*(G \times \mathfrak{b} \times \mathbb{C}^n/G \times B)$$
$$\cong T^*(G \times_B \mathfrak{b} \times \mathbb{C}^n/G) = T^*(\widetilde{\mathfrak{g}} \times \mathbb{C}^n/G).$$

Results for $T^*(\mathfrak{b} \times \mathbb{C}^n)$.

We will thus study $\mu_B^{-1}(0)/B$.

Definition: an element of $\mathfrak{b}$ is *regular* if its stabilizer dimension is minimal. An element in $\mathfrak{b}$ is *semisimple* if it is diagonalizable.

Let $\mu_B^{-1}(0)^{rss}$ be the restriction of $\mu_B^{-1}(0)$ to the regular semisimple locus, i.e., it is the locus where eigenvalues of $\mathfrak{b}$ are pairwise distinct.

Proposition (Im)

$$\mu_B^{-1}(0)^{rss} /\!\!/ B \cong \mathbb{C}^{2n} \setminus \Delta_n, \text{ where}$$
$$\Delta_n = \{(x_1, \ldots, x_n, 0, \ldots, 0) : x_i = x_j \ \forall\, i \neq j\}.$$

Open problems for the Hamiltonian reduction of the cotangent bundle of the enhanced Grothendieck-Springer resolution.

Nevins' Conjecture: $\mu_B^{-1}(0)$ is a complete intersection.

Study

$$\begin{array}{ccccc} & \swarrow & \mu_B^{-1}(0) & \searrow & \\ \mu_B^{-1}(0)/\!\!/_{\chi} B & & \overset{\psi_{\chi,\chi'}}{\dashrightarrow} & & \mu_B^{-1}(0)/\!\!/_{\chi'} B. \\ & \searrow & \mu_B^{-1}(0)/\!\!/ B & \swarrow & \end{array}$$

Why? What is the motivation?

Motivation for open problems.

Let $G := GL_n(\mathbb{C})$ act on $M_n \times \mathbb{C}^n$.

Theorem (Crawley-Boevey, Gan-Ginzburg)

$\mu^{-1}(0)$ is a complete intersection with $n+1$ irreducible components.

Theorem (Nakajima)

$$(\mathbb{C}^2)^{[n]} \cong \mu^{-1}(0)/\!\!/_{\det} G \overset{\cong}{\dashrightarrow} \mu^{-1}(0)/\!\!/_{\det^{-1}} G$$

$$\mu^{-1}(0)/\!\!/_{\det} G \longrightarrow \mu^{-1}(0)/\!\!/ G \cong S^n(\mathbb{C}^2) \longleftarrow \mu^{-1}(0)/\!\!/_{\det^{-1}} G$$

The end.

Thank you. Questions?

If Q is a quiver with at most 2 pathways, then all classical semi-invariant techniques are applicable!

Let $Q = (Q_0, Q_1)$ be an arbitary quiver (where cycles are allowed) and let β be a dimension vector. Choose a set $v_1, \ldots, v_n, w_1, \ldots, w_m \in Q_0$ of vertices (possibly repeating) such that

$$\sum_{i=1}^{n} \beta(v_i) = \sum_{j=1}^{m} \beta(w_j). \tag{1}$$

Let $W \in Rep(Q, \beta)$ be a general representation and consider

$$M : \bigoplus_{i=1}^{n} W(v_i) \longrightarrow \bigoplus_{j=1}^{m} W(w_j),$$

where $M = (m_{ij})$, with each m_{ij} being a linear combination of a general representation of paths in Q from v_i to w_j, including the zero path which corresponds to the zero matrix and the identity matrix if $v_i = w_j$.

Classical technique, 2001.

Theorem (Domokos-Zubkov)

Polynomial coefficients of the determinant of M are in the algebra $\mathbb{C}[Rep(Q,\beta)]^{SL_\beta}$. *Choose all possible combination of vertices satisfying* (1) *and all possible combination of representations of paths to obtain polynomial generators of* $\mathbb{C}[Rep(Q,\beta)]^{SL_\beta}$.

Take home message from this technique: works for any quiver!

Classical technique, 2001.

Example

Suppose Q: $\overset{1}{\bullet}\circlearrowright a$ and $\beta = 2$.
Let $W(a) = (a_{ij})$ be a general representation of $Rep(Q, \beta)$.
Let $n = m = 1$ with $v_1 = w_1 = 1$.
Let $M : W(1) = \mathbb{C}^2 \longrightarrow W(1) = \mathbb{C}^2$, where $M = (tW(a))$.
Then $\det(M) = t^2 \det(W(a)) \Rightarrow \det(W(a))$ is an invariant.
Now let $n = m = 2$ with $v_1 = v_2 = w_1 = w_2 = 1$.
Then $M : \mathbb{C}^2 \oplus \mathbb{C}^2 \longrightarrow \mathbb{C}^2 \oplus \mathbb{C}^2$, and let

$$M = \begin{pmatrix} sW(a) & t\,\mathrm{I}_2 \\ u\,\mathrm{I}_2 & v\,\mathrm{I}_2 \end{pmatrix} = \begin{pmatrix} sa_{11} & sa_{12} & t & 0 \\ sa_{21} & sa_{22} & 0 & t \\ u & 0 & v & 0 \\ 0 & u & 0 & v \end{pmatrix},$$

where s, t, u, v are formal variables.

Classical technique, 2001.

Example (continued)

Then

$$\det(M) = t^2u^2 - (a_{11} + a_{22})stuv + (a_{11}a_{22} - a_{12}a_{21})s^2v^2,$$

and $\mathrm{tr}(W(a)) = a_{11} + a_{22}$ is also an invariant polynomial.
Thus, $\mathbb{C}[Rep(Q, \beta)]^{SL_\beta} = \mathbb{C}[\mathrm{tr}(W(a)), \det(W(a))]$.
Coincides with the classical result that generators of the ring of invariant polynomials are precisely the coefficients of the characteristic polynomial of $W(a)$.