AUSTRALIAN RESEARCH COUNCIL
Discovery Early Career Researcher Award
Proposal for funding commencing in 2015

DE

PROJECT ID: DE150101415

First Investigator: Dr Peter McNamara

Admin Org: The University of Sydney

Total number of sheets contained in this Proposal: 35

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CERTIFICATION

Certification by the Deputy/Pro Vice-Chancellor (Research) or their delegate or equivalent in the Administering Organisation

I certify that—

- I have read, understood and complied with the *Funding Rules for schemes under the Discovery Program for the years 2014 and 2015*, read in conjunction with *Part D - Scheme specific rules for Discovery Early Career Researcher Award for funding commencing in 2015* (the Funding Rules) for this scheme and, to the best of my knowledge all details provided in this Proposal form and in any supporting documentation are true and complete in accordance with these Funding Rules.
- Proper enquiries have been made and I am satisfied that the *Discovery Early Career Researcher Award* (DECRA) Candidate meets the requirements specified in the Funding Rules for this scheme, including having been awarded a PhD on or after 1 March 2009 or, commensurate with a period of eligible career interruption, on or after 1 March 2005.
- Upon request from the ARC, this organisation will provide evidence to support a career interruption justification in relation to the PhD Award date.
- I will notify the ARC if there are any changes to the DECRA Candidate after the submission of this Proposal.
- To the best of my knowledge, all Conflicts of Interest relating to parties involved in or associated with this Proposal have been disclosed to the Administering Organisation, and, if the proposal is successful, I agree to manage all Conflicts of Interest relating to this Proposal in accordance with the *Australian Code for the Responsible Conduct of Research (2007).*
- I have obtained the agreement, attested to by written evidence, of all the relevant persons and organisations necessary to allow the Project to proceed. This written evidence has been retained and will be provided to the ARC if requested.
- This Proposal is not substantially aimed at understanding or treating a human disease or health condition (as per the ARC definition of Medical and Dental Research located on the ARC website).
- This Proposal does not duplicate Commonwealth-funded research including that in a Commonwealth-funded Research Centre.
- If the Proposal is successful, I am prepared to have the Project carried out as set out in this Proposal and agree to abide by the terms and conditions of the Funding Rules and Funding Agreement for this scheme round for funding commencing in 2015.
- The Project can be accommodated within the general facilities in this organisation and, if applicable, within the facilities of other relevant organisations specified in this Proposal, and sufficient working and office space is available for any proposed additional staff.
- This organisation supports this Proposal and, if successful, will provide the DECRA Candidate with an appropriate appointment for the duration of the Award.
- All funds for this Project will only be spent for the purpose for which they are provided.
- The contributions to be provided by this organisation will not be sourced from Commonwealth competitive research funding.
- The project will not be permitted to commence until appropriate ethical clearance(s) has/have been obtained and all statutory requirements have been met.
- I consent, on behalf of all the parties, to this Proposal being referred to third parties, who will remain anonymous, for assessment purposes.
- To the best of my knowledge, the Privacy Notice appearing at the top of this Proposal form has been drawn to the attention of the DECRA Candidate whose personal details have been provided at the Personnel section.
- I consent, on behalf of all the parties, to the ARC copying, modifying and otherwise dealing with information contained in the Proposal.
- I understand that it is an offence under the *Criminal Code Act 1995* to provide false or misleading information.

PART A - Administrative Summary (DE150101415)

A1. If this proposal is successful, which organisation will it be administered by?

Administering Organisation Name

The University of Sydney

A2. Proposal Working Title

(Provide a short working title of no more than 75 characters (10 words). Avoid the use of quotation marks and all upper case characters.)

Higher Representation Theory

A3. Person Participant Summary

	Person number	Family name	First name	Current organisation
1	1	McNamara	Peter	The University of Sydney

	Relevant organisation for this proposal	Role
1	The University of Sydney	Discovery Early Career Researcher Award

A4. Organisation Participant Summary

	Organisation number	Short name	Name	Role
1	1	USyd	The University of Sydney	Administering Organisation

A5. Proposal Summary

(In no more than 750 characters (approx. 100 words) of plain language, summarise aims, significance, expected outcomes and benefits of the project. Please refer to the Instructions to Applicants for further information.)

Representation Theory is a field of mathematics with applications across the breadth of mathematical study in fields as diverse as number theory and physics. The study of higher (or categorical) representation theory is a modern set of tools that provides new insights into representation theoretic pheonomena. This project studies categorified quantum groups, and in particular the categorifications provided by diagrammatic algebras. The project will seek to further develop the theory of KLR algebras, providing important foundational results for future research to build upon.

A6. Impact Statement

(In no more than 500 characters (approx 75 words), please outline the intended impact of the project. Refer to the Instructions to Applicants for further information.)

This project involves research of the highest international calibre on higher representation theory. Progress in this project will lead to the development of important new tools and techniques. These tools and techniques will have significant applications in increasing our understanding of, and ability to work with, quantum groups and their higher categorical analogues. Flow on applications in related scientific endeavours, such as knot theory and mathematical physics, can be expected.

PART B - Classification and other statistical information (DE150101415)

B1. Strategic Research Priorities

B1.1. Does this proposal fall within one of the Strategic Research Priorities?

(Refer to the Selection Criteria described under Section D4.1 of the Funding Rules for this scheme round and the ARC website for the Strategic Research Priorities.)

Strategic Research Priority Selected

No

B1.2. Select which of the Strategic Research Priorities the proposal falls within, and one or more of the relevant Priority Goals for the designated Strategic Research Priority.

Not applicable for this candidate

B2. Does the proposed project increase national research capacity?

National Research Capacity

Yes

B3. Field of Research (FOR)

	Field of Research (FOR)	Field of Research (FOR) Percent
1	010101 - Algebra and Number Theory	60
2	010103 - Category Theory, K Theory, Homological Algebra	20
3	010104 - Combinatorics and Discrete Mathematics (excl. Physical Combinatorics)	20

B4. Socio-Economic Objective (SEO-08)

	Socio Economic Objective (SEO)	Socio Economic Objective (SEO) Percent
1	970101 - Expanding Knowledge in the Mathematical Sciences	100

B5. Keywords

	Keywords
1	Representation Theory
2	Quantum Groups
3	Categorification

B6. If the proposed research involves international collaboration, please specify the country/ies involved.

	International Collaboration Country Name
1	United States of America
2	Canada

PART C - Research Opportunities and Performance Evidence (ROPE) (Dr Peter McNamara)

C1. Details on your career and opportunities for research over the last 5 years

(Write a maximum of 5250 characters (approx. 750 words). Please detail your career and opportunities over the last 5 years. Please refer to the Instructions to Applicants for the required content and formatting.)

Over the last five years, my career path has been:

Massachusetts Institute of Technology, PhD, awarded June 2010

During my PhD I worked at the interface between number theory and representation theory under the supervision of Ben Brubaker, producing a thesis titled "Metaplectic Whittaker Functions". While there I was immersed in the very active research environment in place at MIT and I received a thorough training in cutting edge techniques in representation theory.

Stanford University, September 2010 - June 2013

During this period I held the prestigious position of a Szego Assistant Professor.
This is a job typically given to the most promising newly graduated students. During this period of time, I had a teaching load of four courses per year, each for the duration of one academic quarter. The rest of my time was devoted to research. In addition to the support provided by Stanford University, I applied for and received an AMS-Simons Travel Grant. This proved very useful in allowing me to travel to conferences and initiate some important collaborative projects.

Sydney University, July 2014 - present

I am currently a Research Fellow in the Department of Mathematics and Statistics at the University of Sydney, the position being funded by a grant of Professors Gus Lehrer and Ruibin Zhang. This position carries no official teaching or administrative duties.

I have been fortunate to have no career interruptions in the past five years. During this time period, I have five papers that have either been published or in press. In addition, I have three additional preprints on the ArXiv submitted for publication. The majority of these papers have appeared or will appear in journals of the highest calibre. For example I have papers in Duke Mathematical Journal and Journal für die reine und angewandte Mathematik (Crelle's Journal) which are A* ranked journals under the ARC journal ranking system. Following the culture at MIT and Stanford, I have always strived to ensure that each paper produced is a mature and complete body of work, providing a significant contribution to the research literature in its own right.

I have been invited to speak about my work at a number of international conferences, as well as departmental seminars and colloquia, see C.2 for more details. I have been active internally within departments arranging informal learning and seminar series. I have been active and assiduous in completing my duties to the academic community as a referee.

C2. Significant Research Outputs

(Please attach a PDF with a list of your significant research outputs (4 A4 pages maximum). Provide your research outputs split into the following categories:

i. scholarly books;
ii. scholarly book chapters;
iii. edited books;
iv. refereed journal articles;
v. conference submissions (e.g. papers, invited presentations and posters); and
vi. other (e.g. major exhibitions, compositions or performances).

Asterisk the research outputs relevant to this Proposal.)

Items that appear with an asterisk are directly relevant to the project at hand.

Refereed Journal Articles

P.J. McNamara, *Factorial Grothendieck Polynomials*, Electron. J. Combin., **13** (2006), Research Paper 71, 40 pp. (electronic). arXiv:math/0508192

P.J. McNamara, *Metaplectic Whittaker Functions and Crystal Bases*, Duke Math Journal, **156**, (2011), no 1, 1–31. arXiv:0907.2675.

P.J. McNamara, *Principal Series Representations of Metaplectic Groups over Local Fields*, Multiple Dirichlet Series, L-functions and Automorphic Forms. Birkhauser Progress in Math. **300**, (2012), 299–327. arXiv:0911.2274.

J. East and P.J. McNamara, *On the Work Performed by a Transformation Semigroup*, Austral. J. Combin., **49**, (2011), 95–109.

*P.J. McNamara, *Finite Dimensional Representations of Khovanov-Lauda-Rouquier Algebras I: Finite Type*, arXiv:1207.5860. Accepted for publication 29-07-2013, Journal für die reine und angewandte Mathematik.

*J. Brundan, A. Kleshchev and P.J. McNamara, *Homological Properties of Finite Type Khovanov-Lauda-Rouquier Algebras*, arXiv:1210.6900. Accepted for publication 18-08-2013, Duke Math Journal.

Conference Submissions (Invited Presentations)

12/2013 The Geometry of MV Cycles, *Topology and Representation Theory at Kioloa*, ANU Kioloa Campus, NSW, Australia.

11/2013 * Affine PBW bases and KLR algebras, *Representation Theory in Geometry, Topology and Combinatorics*, University of Melbourne, VIC, Australia.

04/2013 * Representations of KLR algebras, *Lie groups, Lie algebras and their representations*, University of Oregon, OR, USA.

04/2013 Understanding the Chinta-Gunnels action, *Combinatorics, Multiple Dirichlet Series and Analytic Number Theory*, ICERM, RI, USA.

01/2013 * Finite dimensional representations of KLR algebras, *Joint Mathematics Meetings*, San Diego, CA, USA.

12/2012 * Representations of KLR algebras, *Catégorie O: géométrie et catégorification*, Luminy, France.

02/2012 Some Representation Theory of Metaplectic Groups, *Lie Theory Workshop on Quantum Groups*, Stanford, CA, USA.

11/2010 The Casselman-Shalika formula in the metaplectic setting, *Automorphic representations, automorphic forms on covering groups*, Hakuba, Japan.

06/2010 Crystals and metaplectic Whittaker functions, *Quantum Groups, Crystal Graphs and Whittaker Functions*, Banff International Research Station, Alberta, Canada.

06/2009 p-adic Integration, *Fourth Workshop on Multiple Dirichlet Series*, Stanford University, CA, USA.

Other - Preprints on Arxiv

P.J. McNamara, *Factorial Schur Functions via the Six Vertex Model*, `arXiv:0910.5288`.

P.J. McNamara, *The Metaplectic Casselman-Shalika Formula*, `arXiv:1103.4653`.

D. Bump, P.J. McNamara and M. Nakasuji, *Factorial Schur functions and the Yang-Baxter equation*, `arXiv:1108.3087`.

Other - Invited Departmental Talks

10/2013 * Representations of KLR algebras, *Seminar*, Australian National University, ACT, Australia.

08/2013 * Representations of KLR algebras, *Seminar*, University of Sydney, NSW, Australia.

06/2013 * Categorifying Quantum Groups, *Seminar*, Monash University, VIC, Australia.

05/2013 * Representations of KLR algebras, *Algebra & Discrete Mathematics Seminar*, University of California, Davis, CA, USA.

03/2013 * Representations of KLR Algebras, *Colloquium*, Aarhus University, Aarhus, Denmark.

01/2013 * Representation theory of KLR algebras, *Seminar*, HKU, Hong Kong.

12/2012 * KLR Algebras, *Seminar*, Bonn University, Germany.

09/2012 * Finite dimensional representations of KLR algebras, *Algebra and Combinatorics Seminar*, Loyola University, IL, USA.

04/2012 * Finite dimensional representations of KLR algebras, *Algebra-Geometry-Combinatorics Seminar*, UIUC, IL, USA.

08/2011 Metaplectic Groups, *Seminar*, University of Melbourne, VIC.

02/2011 The Casselman-Shalika formula in the metaplectic setting, *Number Theory Seminar*, Stanford, CA.

08/2010 Factorial Schur polynomials from the viewpoint of the six-vertex model, *Groups and Combinatorics Seminar*, UWA, WA.

12/2009 Representations of metaplectic groups and their Whittaker functions, *Lie Groups Seminar*, MIT, MA.

04/2008 Arizona Winter School Redux, *Number Theory Seminar*, MIT, MA.

C3. Statement on your contributions to the research field of this Proposal

(Please attach a PDF detailing your contributions to the research field and evidence of your performance which demonstrate your capacity to undertake the proposed research (1 page maximum). This could include your PhD research and related publications and presentations, subsequent contributions where applicable as well as conference organisation and learned societies membership.)

C3. STATEMENT ON YOUR CONTRIBUTIONS TO THE RESEARCH FIELD OF THIS PROPOSAL

In terms of published works, my contributions to the research literature that are directly related to the project at hand are my sole-authored paper "Finite Dimensional Representations of Khovanov-Lauda-Rouquier Algebras I: Finite Type" and my paper with Brundan and Kleshchev "Homological Properties of Finite Type Khovanov-Lauda-Rouquier Algebras". Both of these are important bodies of work that have been accepted for publication at top journals, namely Journal für die Reine und Angewandte Mathematik (Crelle's Journal) and Duke Mathematical Journal respectively. These journals were rated A* in the ERA journal rankings.

In the first of these papers, I generalised work of Kleshchev and Ram, and Hill, Mondragon and Melvin to give a satisfactory theory classifying irreducible representations of finite type KLR algebras and their connection to PBW bases. As a consequence I was able to answer an open problem concerning the positivity of a transition matrix between PBW and canonical bases, and prove that finite type KLR algebras have finite global dimension.

In joint work with Brundan and Kleshchev, we build on the ideas of my previous sole-authored paper, developing a more mature homological theory, introducing standard modules and BGG reciprocity for finite type KLR algebras.

Over the past couple of years, I have received many invitations to speak about my work to date on KLR algebras. As a result of having attended these conferences, I have been able to connect with many leading researchers in the area. This puts me in the position where I have a strong capacity to successfully undertake the research outlined in this proposal.

I have a second major research project, on Whittaker functions for metaplectic groups. While not directly related to the project at hand, there are some common threads, such as the appearance of crystal combinatorics and in particular the combinatorics of Mirkovic-Vilonen polytopes. The experience gained by working on this project with the attendant facility in Lie-theoretic combinatorics that I have developed will stand me in good stead to complete the proposal at hand.

D1. Please upload a Project Description as detailed in the Instructions to Applicants in no more than eight A4 pages and in the required format

Attached PDF

Project Title

Homological Properties of KLR Algebras.

Aims and Background

Aims. The aim of this project is to prove four conjectures in the theory of KLR algebras regarding their relationship with PBW bases, their homological properties and the categorification of reflection functors. KLR algebras are a central topic in modern representation theory due to the way in which they categorify quantum groups. We will now state these conjectures, referring the reader to later on for further details.

Conjecture 1. *The classes of the modules in a cuspidal system (in the sense of* [Kle]*), under the isomorphism (2), are equal to elements of a dual PBW basis.*

Conjecture 2. *Affine type KLR algebras are affine quasi-hereditary. In particular, we can construct a family of standard modules categorifying the PBW basis, which satisfy an upper-triangular* Ext*-vanishing condition.*

Conjecture 3. *Affine KLR algebras are affine cellular in the sense of* [KX12].

Conjecture 4. *Let $\nu \in \mathbb{N}I$ and $i \in I$ be such that $s_i\nu \in \mathbb{N}I$. There is a functor $\mathbb{T}_i$ which provides an equivalence of categories*

$$\{M \in R(\nu)\text{-}fmod \mid \mathrm{Res}_{i,\nu-i}(M) = 0\} \cong \{N \in R(s_i\nu)\text{-}fmod \mid \mathrm{Res}_{s_i\nu-i,i}(N) = 0\}$$

and categories the algebra isomorphism of the quantum group commonly denoted T_i.

Background. Quantum groups are remarkable mathematical objects which were introduced by Drinfeld and Jimbo in the 1980s. The particular quantum groups we are interested in are canonical deformations of universal enveloping algebras, which had been and still are a fundamental object in Lie theory. It was quickly realised that these quantum groups posessed remarkable structure previously unseen in the classical theory - not the least of which was the construction by Kashiwara and Lusztig of a canonical basis. This canonical basis, completely invisible in the classical picture, has lead to much activity in the subject in the last twenty years.

The KLR algebras which are the principal object of investigation in this project arise when one categorifies these quantum groups. Categorification is a process whereby an algebra (in this case the quantum group) is realised as the Grothendieck group of a tensor category or a 2-category (in this case a category of modules for KLR algebras). The particular categorification under investigation here has its roots in Lusztigs geometric approach to canonical bases via perverse sheaves. It has the significant advantage of replacing difficult geometry by combinatorial algebra which is more amenable to computations and exploration.

Just as the theory of Kac-Moody Lie algebras is divided into finite, affine and hyperbolic type, of which the first two are the most important, so is the theory of KLR algebras. The usual experience in this subject is that the process of finding the correct affine analogue of a known finite type phenomenon is highly nontrivial, and the process of doing so often provides us with extra understanding about the finite type case as well.

Khovanov-Lauda-Rouquier algebras (henceforth KLR algebras) are a family of associative algebras associated to any Kac-Moody Lie algebra $\mathfrak{g}$ by Khovanov and Lauda [KL09, KL11] and Rouquier [Rou], for the purpose of categorifying quantum groups. Subsequently, a generalisation to Borcherds algebras [KOP] as well as a super analogue [KKT] has appeared. The KLR algebras are a family of $\mathbb{Z}$-graded algebras $R(\nu)$ indexed by nonnegative integer linear combinations of simple roots of $\mathfrak{g}$, together with nonunital inclusions $R(\lambda)\otimes R(\mu) \hookrightarrow R(\lambda+\mu)$.

Understanding the representation theory of KLR algebras is a significant problem in higher representation theory. Due to the prominent position that the KLR relations play in the definition of a 2-categorical version of a quantum group (or Lie algebra), it is necessary to understand the representation theory of KLR algebras in order to understand the higher categorical picture.

The fundamental theorem about KLR algebras from [KL09] is the existence of a pair of dual isomorphisms

$$\bigoplus_\nu K_0(R(\nu)\text{-pmod}) \cong U_q(\mathfrak{g})^+ \tag{1}$$

$$\bigoplus_\nu K_0(R(\nu)\text{-fmod}) \cong (U_q(\mathfrak{g})^+)^* \tag{2}$$

The categories involved are the categories of finitely generated projective and finite dimensional $R(\nu)$-modules respectively, while the right hand side of these isomorphisms are the $\mathbb{Z}[q^{\pm 1}]$ forms of the positive part of the corresponding quantum group and its $\mathbb{Z}[q^{\pm 1}]$-linear graded dual. This is the precise sense in which the KLR algebras categorify the quantum group. Due to the ability to reconstruct the entire quantum group from its upper part via a Drinfeld construction, the restriction to the upper part should not be considered a drawback.

When the underlying Cartan datum is symmetric, then there is a geometric interpretation of KLR algebras due to [Rou12, VV11, Mak] directly relating them to Lusztig's construction [Lus91] of the canonical basis of $U_q(\mathfrak{g})^+$ via perverse sheaves on moduli stacks of quiver representations. This arises via KLR algebras being isomorphic to certain convolution algebras in equivariant Borel-Moore homology. Away from symmetric type, the KLR algebras are more mysterious and in fact it is known [Tsu] that the natural basis of $U_q(\mathfrak{g})^+$ given by indecomposable projectives that one obtains from the KLR categorification differs from the canonical basis. This latter difference between the KLR and canonical bases persists in positive characteristic, even in symmetric type, but this is explained [Wil] by the presence of torsion in intersection cohomology.

It is desirable to classify the irreducible representations of KLR algebras. In the literature, there are various classifications available [KR11, HMM12, LV11, BKOP, McN, TW]. My results on this topic generalise the previous work of Kleshchev and Ram, and Hill, Melvin and Mondragon. We now discuss these, as they provide motivation for the conjectures which we will prove in this project.

Consider the case where $\mathfrak{g}$ is a finite dimensional semisimple Lie algebra. To state the classification from [McN], we first need to fix once and for all a convex ordering $\prec$ on the set Φ^+ on the set of positive roots. Write $\{\Phi^+ = \alpha_1 \prec \alpha_2 \prec \ldots \prec \alpha_N\}$. This datum is equivalent to that of a reduced decomposition of the longest element in the Weyl group. Once such an ordering is chosen, it determines a PBW basis of $U_q(\mathfrak{g})^+$ and a dual PBW basis of $(U_q(\mathfrak{g})^+)^*$, the latter of which consists of ordered monomials in a family of elements $\{E_\alpha^* \mid \alpha \in \Phi^+\}$.

One of the main theorems of [McN] is (after fixing a choice of convex ordering, which determines the elements E_α^*):

Theorem 5. [McN, Theorem 3.1] *For each positive root α, there exists a simple representation S_α of $R(\alpha)$ such that*

(1) *The image of the class of S_α under the isomorphism (2) is the dual PBW basis element E_α^*.*
(2) *For each $\mathbf{m} = (m_1, \ldots, m_N) \in \mathbb{N}^N$, the representation $\overline{\Delta}(\mathbf{m}) = S_{\alpha_1}^{\circ m_1} \circ S_{\alpha_2}^{\circ m_2} \circ \cdots \circ S_{\alpha_N}^{\circ m_N}$ has a unique irreducible quotient $L(\mathbf{m})$.*
(3) *The simple representations $L(\mathbf{m})$ thus constructed form a complete set of representatives of isomorphism classes of simple representations of KLR algebras.*
(4) *The representation $\nabla(\mathbf{m}) = S_{\alpha_N}^{\circ m_N} \circ S_{\alpha_{N-1}}^{\circ m_{N-1}} \circ \cdots \circ S_{\alpha_1}^{\circ m_1}$ has $L(\mathbf{m})$ as its socle.*
(5) *Any simple constituent $L(\mathbf{m}')$ of a composition series of $\overline{\Delta}(\mathbf{m})$ or $\nabla(\mathbf{m})$ satisfies $\mathbf{m} \leq \mathbf{m}'$ for the lexicographical ordering on $\mathbb{N}^N$. Furthermore $L(\mathbf{m})$ appears in such a composition series with multiplicity one.*

Here there is one parametrisation of the set of irreducible modules for each choice of convex order. So one is naturally led to ask how these parametrisations for different choices of convex orderings relate to each other. An answer is given in terms of the combinatorics of Mirkovic-Vilonen polytopes, which were introduced by Kamnitzer [Kam10] in the context of studying the geometry of the affine grassmannian. This result is due to Tingley and Webster [TW], and in joint work with Muttiah and Tingley [MMT], we provide, among other things, an exposition optimised for the case where $\mathfrak{g}$ is finite dimensional (the Tingley-Webster work is in greater generality).

In addition, I proved the following theorem, answering a question of Kashiwara and generalising a contemporary result of Kato [Kat, Theorem A].

Theorem 6. [McN, Theorem 4.7] *Suppose the underlying Cartan datum is of finite type. Then the global dimension of $R(\nu)$ is $|\nu|$ (and in particular it is finite).*

In [KKK], a tensor functor from KLR modules to representations of quantised affine algebras is constructed. The above theorem is put to use as an important technical tool in proving the exactness of this functor under an ADE condition.

The purpose of my joint paper with Brundan and Kleshchev [BKM], again working in finite type, is to build on the results of [McN] and develop a theory of standard modules. Again, a convex order is fixed, and for each $\mathbf{m} \in \mathbb{N}^N$, a standard module $\Delta(\mathbf{m})$ with simple head $L(\mathbf{m})$ is constructed out of the maximal self-extension of the S_α. The main theorem of [BKM] is the following homological property of these modules.

Theorem 7. (1) *We have that $\mathrm{Ext}^d(\Delta(\mathbf{m}), V) = 0$ for all $d \geq 1$ and any finitely generated $R(\nu)$-module V all of whose irreducible subquotients are of the form $q^n L(\mathbf{n})$ with $\mathbf{n}$ not greater than $\mathbf{m}$ in lexicographical order.*
(2) *We have that*

$$\dim \mathrm{Ext}^d(\Delta(\mathbf{m}), \overline{\Delta}(\mathbf{n})^{\circledast}) = \begin{cases} 1 & \text{if } d = 0 \text{ and } \mathbf{m} = \mathbf{n}, \\ 0 & \text{otherwise,} \end{cases}$$

for all $d \geq 0$ and $\mathbf{m}, \mathbf{n} \in \mathbb{N}^N$, where $^{\circledast}$ denotes the dual of a module and multiplication by q denotes a grading shift.

The following generalisation of a theorem of Lusztig [Lus90, Corollary 10.7] appears as a corollary to Theorem 5. A BGG reciprocity theorem is also proved in [BKM], giving a second interpretation of the coefficients below.

Theorem 8. *In a quantised enveloping algebra of finite symmetric type, consider the transition matrix from the canonical basis of $U_q(\mathfrak{g})^+$ to the PBW basis of $U_q(\mathfrak{g})^+$. This matrix is upper triangular, with ones along the diagonal, and the entries have an interpretation as the multiplicity of an irreducible module in a Jordan-Holder series. In particular the entries all lie in $\mathbb{N}[q^{\pm 1}]$.*

A weak version of Theorem 5 in affine type is already known [Kle]. What is missing, and this is the most important part, is control over the cuspidal modules (these are the modules denoted S_α above) and their imaginary analogues. In particular, there is no connection with the theory of PBW bases.

1. Detailed information about the aims

Conjectures 1 and 2 are about establishing the relationship between PBW bases and KLR algebras in affine type. The easier finite type analogue of this problem is the results presented in [McN, BKM], and in [Kat] by geometric means in types ADE.

Kleshchev [Kle] and Tingley and Webster [TW] have given a classification of irreducible modules of affine type KLR algebras in terms of a *cuspidal system*. The cuspidal system is a particular set of irreducible modules of KLR algebras from which all others are constructed by a process of induction and taking quotients. Very little is known about their structure.

Conjecture 1 will help us understand more about these cuspidal representations, and connect the theory of KLR algebras in affine type to the important theory of PBW bases. Successful resolution of this conjecture will enable greater understanding of PBW bases. This will include understanding PBW bases where the starting point is an arbitrary convex order on the root system, as opposed to the more narrow doubly infinite word that has often been taken as the starting point in the literature to date.

A particular corollary of Conjecture 1 is a proof of the following conjecture:

Conjecture 9. *In a quantised enveloping algebra of affine symmetric type, consider the transition matrix from the canonical basis of $U_q(\mathfrak{g})^+$ to the PBW basis of $U_q(\mathfrak{g})^+$. This matrix is upper triangular, with ones along the diagonal, and the entries have an interpretation as the multiplicity of an irreducible module in a Jordan-Holder series. In particular the entries all lie in $\mathbb{N}[q^{\pm 1}]$.*

The affine case is significantly harder than the finite type case, which is known due to Lusztig [Lus90] under the additional technical restriction that the PBW bases are adapted to the orientation of the quiver, and independently due to myself [McN] and Kato [Kat] for all PBW bases in symmetric finite type.

We also propose to understand the homological properties of finite type KLR algebras. Unlike the finite type result [McN, Theorem 4.7], it is known that affine type KLR algebras in general have infinite homological dimension. However we still expect the existence of a theory of standard modules, similar to that developed in [BKM] in the finite type case. Conjecture 2 makes this more precise, with the exception of the notion of being affine quasi-hereditary, for which it is not currently known what the best definition is.

There is a notion of a cellular algebra due to Graham and Lehrer [GL96] which has proved fruitful over the subsequent years as it was discovered that many naturally occurring algebras are cellular. KLR algebras are not cellular in this narrow sense, but there is a related notion of an affine cellular algebra due to Koenig and Xi [KX12].

It is known [KLM13, KL], that KLR algebras of finite type are affine cellular in this sense. From a practical point of view, this property is very similar to the homological properties established in the papers [McN] and [BKM]. Naturally we are then led to investigate Conjecture 3.

It is possible that the KLR algebras will not be affine cellular in the sense of [KX12]. In such a situation, we can modify the conjecture to ask what is the appropriate replacement of the notion of affine cellular to consider that encapsulates the (nice) homological properties of affine KLR algebras.

We hope that an answer to this question will emerge as a by-product into our investigations of standard modules for affine KLR algebras.

This second major aim of this project is to construct reflection functors for KLR algebras. These reflection functors should provide the functors in the conjectural equivalences that appear inConjecture 4.

This conjecture follows thematically from the existence of related reflection functors in the representation theory of quivers [BGP73] and preprojective algebras [IR11, BK12].

This conjecture has already been addressed in finite symmetric type in work of Kato [Kat], which is heavily dependent on the geometric interpretation of KLR algebras. Novel techniques will be needed to go beyond the work of Kato. A potential first subproblem towards proving this conjecture is to understand how to give a purely algebraic version of the construction of Kato.

Further progress beyond the narrow applicability of Kato's work is necessary for applications. One place where the presence of a mature theory of reflection functors is known to be useful is in the previous project relating PBW bases and KLR algebras described above. For example the cuspidal representations for real roots can conjecturally be constructed inductively by applying reflection functors to a one dimensional representation. Another place where some functoriality would be useful is in the work of Tingley and Webster [TW] where they have to come up with some seemingly artificial ways to work around the lack of functoriality of certain constructions, that reflection functors would provide.

Tilting modules are known to be a source of derived equivalences, and understanding tilting modules for KLR algebras is one approach which may prove fruitful in attacking Conjecture 4. Tilting modules for KLR algebras would also be useful to understand in their own right. The study of tilting modules for KLR algebras is one project which would be particularly suitable for a PhD thesis, also training the next generation of researchers.

Project Quality and Innovation

The field of higher, or categorical, representation theory is currently a very active field in mathematics. This is evidenced by the exciting results appearing on a regular basis, for example

[BKM, Kat, KKK, Kle, KL, KLM13, KM, Mak, McN, TW, Wil] have all been announced in the past two years. It is also evidenced by the number of international conferences in the field, for example there are significant conferences at Montreal, Canada, Corsica, France and Edinburgh, Scotland in 2014 organised under the auspices of the Centre de Recherches Mathématiques, the Institut d'Etudes Scientifiques de Cargese and jointly by the London Mathematical Society and the Clay institute respectively.

There are top mathematicians worldwide currently active in and taking a strong interest in this young and upcoming field, for example Kashiwara (RIMS Kyoto), Khovanov (Columbia University), Rouquier (UCLA), Vasserot (Paris), Williamson (Max Plank Institute - Bonn).

The conjectures that this project will solve are innovative and new. Completion of this project, especially the construction of a mature theory of reflection functors, will create new techniques that will transform this field of study.

Research Environment

I will undertake this DECRA at the University of Sydney. The Department of Mathematics and Statistics at the University of Sydney has a particularly strong and active Algebra group. This group has a regular seminar series that attracts speakers of international renown, fed by the stream of international visitors who come to the department to collaborate. Being part of this research group will provide myself with a supportive and productive environment locally with a number of experienced people that I will be able to be in regular face-to-face contact with to fruitfully exchange ideas. Indeed, there is a lot of interest amongst this algebra group on the topics which I plan to work on. In particular, the research interests of Professors Lehrer, Mathas and Zhang complement my own interests nicely.

The University of Sydney offers a world-class research environment, with a well-equipped library with both print and online resources. There will also be any necessary computing facilities available for my use.

Dissemination and promotion of research outcomes will occur by submitting papers to the arXiv and journals, and by presentation of results at international conferences. The local research environment provides support to enable this to happen.

Feasibility and Benefit

I have a strong record and am considered one of the world leaders in this field, having been invited to a number of international conferences as a result of this status. I have collaborated with other leading experts such as Brundan and Kleshchev, with published papers in top quality journals.

This project is a challenging project but at the same time is a natural evolution of what has already been achieved recently by myself and others. As such I am uniquely placed as the best person in the world to complete this research, and I believe I can achieve this within the three year time period of the DECRA.

The research facilitated by the support of the DECRA will help attract international researchers to visit Australia, and will also support PhD and honours students. In this way, the mathematical reputation of the University of Sydney is strengthened. Australia's research activity will be enhanced through the attraction of international visitors, while the educational reprutation of Australian universities will also be enhanced by the training that our students will receive in an active research environment.

DECRA Candidate

Apart from a small amount of teaching I will do, all my time (85%) will be spent on the project.

Management of Data

Research data and related materials will be retained in accordance with the Universitys *Research Data Management Policy* and *Research Code of Conduct*; research data will be stored on University managed storage infrastructure with access provided to all members of the project team. Research data collections will be made available for reuse by other researchers, unless this is prevented by the requirements of legislation or University policy, or ethical, contractual or confidentiality obligations.

References

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[Tsu] Shunsuke Tsuchioka (mathoverflow.net/users/9661). When does Lusztig's canonical basis have non-positive structure coefficients? MathOverflow. `http://mathoverflow.net/questions/40577` (version: 2010-09-30).

[TW] Peter Tingley and Ben Webster. Mirkovic-Vilonen polytopes and Khovanov-Lauda-Rouquier algebras. `arXiv:1210.6921`.

[VV11] M. Varagnolo and E. Vasserot. Canonical bases and KLR-algebras. *J. Reine Angew. Math.*, 659:67–100, 2011.

[Wil] G. Williamson. On an analogue of the James conjecture. `arXiv:1212.0794`.

D2. Organisational Statement in respect of the Research Environment

(Please provide an Organisational Statement in relation to the Research Environment in no more than 2 A4 pages.

Please outline:

- the extent to which the DECRA project aligns with the existing and/or emerging research strengths of the Administering Organisation;
- the arrangements under which the DECRA Candidate will be supported in a collaborative research environment; and
- the opportunities for the DECRA Candidate to demonstrate the level of independence required to be competitive for research and/or research and teaching pathways at the Administering Organisation during and after the project.

)

D2 – Organisational Statement

The University of Sydney Strategic Plan 2011-15 includes the goals of

1. identifying, developing and supporting talented researchers at all stages of their career,
2. contributing to the cultural, social and economic benefit of Australia and the international community,
3. building areas of research capacity and strength.

These goals coincide with the objectives of the Discovery Early Career Researcher Award, and the University welcomes the opportunity to build research capacity by hosting DECRA holders in areas of strength and strategic importance.

Alignment with existing and/or emerging research strengths of the Administering Organisation

Appointing high quality researchers and developing their research and teaching is a key point to the School's strategic plan. The School has 68 academic and research-only staff including renowned researchers such as Professors Cannon, Dancer, Goldys, Gottwald, Joshi, Lehrer, Mathas, Molev, Rutkowski, Weber and Zhang. The School's staff includes one Laureate Fellow (Joshi), two Australian Professorial Fellows (Mathas and Zhang), five Future Fellows (Gottwald, Henderson, Wechselberger, Tzou, Yang), four Discovery Early Career Researcher Award (DECRA) recipients (Kim, Olver, Ormerod, Vasil) and 1 Australian Postdoctoral Fellow (Atkinson). Awards won by mathematics researchers in the School include the Hannan Medal (Dancer), the Clunies-Ross Award and the Jenks Prize (Cannon), two Humboldt Research Awards (Dancer and Lehrer), the Medal of the Australian Mathematical Society (Henderson, Molev and Mathas), the Pitman Medal for Statistics (Robinson), and the Christopher Heyde Medal (Henderson) and the Leverhulme Fellowship (Dancer, Dullin). Professors Dancer, Joshi and Lehrer are Fellows of the Australian Academy of Science. In addition to the above Fellowships mathematics researchers in the School have been awarded new ARC Discovery grants totaling $3.0m in the past 2 years.

The School attracts an exceptionally strong cohort of talented undergraduate students, research postgraduates and international academic visitors. It currently hosts 59 postgraduate students and 28 honours students are enrolled in 2014. It also attracts a constant stream of high-profile international visitors each year. In the last 12 months the School had over 70 international visitors.

The support for the DECRA Recipient within a collaborative research environment

Algebra is one of the School's research strengths with 5 Professors, one Associate Professor and several research only staff working in this area. Dr McNamara's project, Higher Representation Theory, aligns closely with the research focus of Professors Lehrer and Mathas and he will be well supported and mentored if placed within our School.

Opportunities for the DECRA candidate to demonstrate appropriate career-stage independence during and after completion of the Project.

The University of Sydney is committed to providing DECRA holders with opportunities for professional development, such as researcher training, access to internal funding schemes, and promotion. The University will top up DECRA salaries to match the corresponding University salary scales.

The University will provide the facilities and infrastructure needed for the proposed project, including the Access Grid technology for international collaboration, and the library's comprehensive access to mathematical journals and books.

The applicant will be supported in career development whilst on the DECRA via the School's mentoring program. He will be required to complete the Institute of Teaching and Learning's Principles and Practice of University Teaching and Learning program and the Foundations of Research Supervision program. He will also be given opportunity to develop his lecturing and supervision skills over the three years of the program.

To help Dr McNamara develop his research profile the School will offer a small travel grant of $5000 per year to supplement the award funding to enable him to attend critical conferences and workshops in his area.

D3. Medical and Dental Research Statement

(If applicable, in no more than 750 characters (approx. 100 words), please justify why this Project does not constitute Medical and Dental Research as defined on the ARC website. Refer to the Instructions to Applicants for further information.)

Not Applicable

PART E - Project Cost (DE150101415)

E1. What is the proposed budget for your project?

(Please provide details of the budget proposed for your project.)

Proposal Funding Summary

Total requested budget: $403464

Year 1

Description	**ARC**
Direct Cost	134488
Personnel	119918
DECRA (Dr Peter McNamara)	94512
PhD Student	25406
Travel	14120
Collaboration and Conference - Airfare	2500
Collaboration and Conference - Accommodation	4900
Collaboration and Conference - Per Diem	4970
AustMS Meeting - Airfare	400
AustMS - Accommodation	875
AustMS - Per Diem	475
Other	450
AustMS - Registration Fee	450

Year 2

Description	**ARC**
Direct Cost	134488
Personnel	119918
DECRA (Dr Peter McNamara)	94512
PhD Student	25406
Travel	14120
Collaboration and Conference - Airfare	2500
Collaboration and Conference - Accommodation	4900
Collaboration and Conference - Per Diem	4970
AustMS Meeting - Airfare	400
AustMS - Accommodation	875
AustMS - Per Diem	475
Other	450
AustMS - Registration Fee	450

Year 3

Description	**ARC**
Direct Cost	134488
Personnel	119918
DECRA (Dr Peter McNamara)	94512
PhD Student	25406
Travel	14120

Description	ARC
Collaboration and Conference - Airfare	2500
Collaboration and Conference - Accommodation	4900
Collaboration and Conference - Per Diem	4970
AustMS Meeting - Airfare	400
AustMS - Accommodation	875
AustMS - Per Diem	475
Other	450
AustMS - Registration Fee	450

PART F - Budget Justification (DE150101415)

F1. Justification of funding requested from the ARC

(The ARC budget justification information must not exceed 2 A4 pages.

The justification should indicate how the DECRA Candidate will use the project cost funding each year. This statement should include the need and cost for each item requested from the ARC using the same headings as in the budget at E1. For an example please see Part F of the Instructions to Applicants.

- The justification should be provided for each item under each year using the headings as in the budget at E1. A separate table should be provided for each year with the headings Year 1, Year 2 and Year 3 respectively. Items requested across multiple years, that is, Year 1, Year 2 and/or Year 3, should be listed separately for each year.
- Please justify and explain the need and cost for each item requested from the ARC. Explain why a certain item is necessary for the Project and what it will contribute. For research support personnel please state that a full-time research assistant or technician with a specific level of expertise is required for 'x' months.
- If seeking funding for new equipment, please describe how the equipment will be used and provide details of the manufacturer, supplier, cost and installation based on quotations obtained. Do not supply the quotations.
- Please justify and explain the need and cost of economy domestic and international travel for the DECRA Candidate.

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F1. JUSTIFICATION OF FUNDING REQUESTED FROM THE ARC

Table 1. **Year 1**

Item Requested	Cost	Justification
Personnel		
DECRA Candidate	94512	Salary support for DECRA Candidate to support fulltime research.
Ph.D. student	25406	Funding is requested for a full-time doctoral student to work under my supervision. Tailored to the individual student's tastes and strengths, there are several problems which would make suitable thesis topics; one is defined the end of the Aims and Background section in D1.
Travel		
Collaboration and Conference - Airfare	2500	This project involves collaboration with internationally located mathematicians, and will I will need to travel to work with these collaborators in the most productive manner possible. These include Jon Brundan and Alexander Kleshchev, at the University of Oregon (Eugene, USA), Peter Tingley, at Loyola University (Chicago, USA) and Dinakar Muttiah, at University of Toronto (Toronto, Canada). As part of the dissemination of the results produced from this project, to keep abreast of the latest developments and techniques in the field and to maintain my international standing in the field, I will be needing to travel to conferences. The estimate provided is based on a return round-trip airfare to North America. Travel would involve attendance at the leading conference in my field in the year (the conference schedule is not known this far in advance), as well as collaborative visits to Eugene, Chicago and Toronto.
Collaboration and Conference - Accommodation	4900	This estimate is based on four weeks of accommodation in hotels across North America. This would be divided into one week each at the conference venue, Eugene, Chicago and Toronto.
Collaboration and Conference - Per Diem	4970	This figure is based on the rates set by the University of Sydney for 21 days in the USA and 7 days in Canada. For the purposes of this estimate, I have made the probable assumption that the leading conference which I wish to attend will be located in the USA.
AustMS Annual Meeting - Airfare	400	Attendance at the annual meeting of the Australian mathematics society is the most effective way to engage with the Australian mathematical community.
AustMS Annual Meeting - Accommodation	875	Five nights accommodation to attend the annual meeting.
AustMS Annual Meeting - Per Diem	475	Based on the rates set by the University of Sydney for four days of domestic travel.
Other		
AustMS Annual Meeting - Registration Fee	450	Estimate is based on the 2011 rate - the most recent able to be located.

Table 2. **Year 2**

Item Requested	**Cost**	**Justification**
Personnel		
DECRA Candidate	94512	Same as above
Ph.D. student	25406	Same as above
Travel		
Collaboration and Conference - Airfare	2500	Same as above
Collaboration and Conference - Accommodation	4900	Same as above
Collaboration and Conference - Per Diem	4970	Same as above
AustMS Annual Meeting - Airfare	400	Same as above.
AustMS Annual Meeting - Accommodation	875	Same as above
AustMS Annual Meeting - Per Diem	475	Same as above
Other		
AustMS Annual Meeting - Registration Fee	450	Same as above

Table 3. **Year 3**

Item Requested	**Cost**	**Justification**
Personnel		
DECRA Candidate	94512	Same as above
Ph.D. student	25406	Same as above
Travel		
Collaboration and Conference - Airfare	2500	Same as above
Collaboration and Conference - Accommodation	4900	Same as above
Collaboration and Conference - Per Diem	4970	Same as above
AustMS Annual Meeting - Airfare	400	Same as above.
AustMS Annual Meeting - Accommodation	875	Same as above
AustMS Annual Meeting - Per Diem	475	Same as above
Other		
AustMS Annual Meeting - Registration Fee	450	Same as above

G1. Personal details

(The personal details will be filled out for you automatically. To update any of your personal details in this form, please update your profile accordingly and your details will update automatically in this form.)

Title

Doctor

Family Name

McNamara

First Name

Peter

Person identifier

39672841

Role

Discovery Early Career Researcher Award

G2. Postal address

(The postal address will be filled out for you automatically. To update your postal address, please update your profile accordingly and your postal address will update automatically in this form.)

Postal Address Line 1

School of Mathematic and Statistics

Postal Address Line 2

Carslaw Building F07

Locality

University of Sydney

State

NSW

Postcode

2006

Country

Australia

G3. Are you a current member of the ARC or its selection or other advisory committees?

(This relates only to ARC College of Experts or Selection Advisory Committee members for National Competitive Grants Program funding schemes.)

Current Member of Advisory Committee

No

G4. Current Research Fellowship

Do you hold a current Research Fellowship?

(This includes all ARC Fellowships and Fellowships from other agencies.)

Hold Current Research Fellowship

No

Current fellowships held

Not applicable for this candidate

G5. Please name any Commonwealth-funded Research Centres that you will be associated with as at 1 January 2015.

	Full Legal Name of Centre	Start Date	Cessation Date	Centre Role
1				
2				

	Centre Role if Other
1	
2	

G6. Are you an Indigenous Participant?

Indigenous Participant

No

G7. PhD Qualification

G7.1. Date of PhD Award

(If the day of PhD conferral is not known, please choose the last day of the month and year conferred (e.g. 31/03/10).)

04/06/2010

G7.2. Justification and details of career interruption/s

	Start date	End date	Type of interruption	Was the employment research related?
1				
2				

	Full-time/part-time equivalent FTE of career interruption	Additional details of interruption (e.g. name of institution, country): In no more than 500 characters (approx 75 words) of plain language, summarise details of career interruption.
1		
2		

G7.3. Justification for PhD Equivalent Degree

(If you do not hold a PhD, please provide a justification outlining how your degree meets the requirements of a Doctoral Degree as specified in Level 10 of the Australian Qualifications Framework Second Edition 2013. Please refer to the Instructions to Applicants for further information. The justification must not exceed 1500 characters.)

G8. Qualifications

	Degree/Award	Year	Discipline/Field	Organisation Name
1	PhD	2010	Mathematics	Massachusetts Institute of Technology
2	B.Sc(Hons)	2006	Mathematics	The University of Sydney

	Country
1	United States of America
2	Australia

G9. Current and previous appointment(s)/position(s) – during the past 10 years

	Position	Organisation Name	Department	Year Appointed
1	Research Fellow	The University of Sydney	Mathematics and Statistics	2013
2	Szego Assistant Professor	Stanford University	Mathematics	2010

	Continuity	Employment Kind	Current
1	Contract	Full Time	Yes
2	Contract	Full Time	No

G10. Organisational affiliation for eligibility purposes

(Will you hold an appointment at the Administering Organisation with effect on the date of the commencement of the Discovery Early Career Researcher Award?)

Affiliation

Yes

G11. Citizenship/Residency Details

(Please note, that the Australian citizenship status as well as the list of countries that you have citizenship of is populated from your profile.)

Australian Citizen?

Yes

Countries of Citizenship

Australia

Country of residence Name

Australia

Current Australian residency status

Permanent

PART H - Research Support (DE150101415)

H1. Research Support for the DECRA Candidate

(Provide details of requested and awarded research funding (ARC and other agencies in Australia and overseas) for the years 2013-2017 inclusive. That is, list all projects/proposals/awards/fellowships awarded or requests submitted involving the DECRA candidate for funding. Please refer to the Instructions to Applicants for submission requirements.)

Description (all named investigators on any Proposal or grant/ project/ fellowship in which a participant is/was involved, project title, source of support, scheme and round)	**Same Research Area** (Yes/No)	**Support Status** (Requested/Current/Past)	**Proposal/ Project ID** (if applicable)	**2013** ($'000)	**2014** ($'000)	**2015** ($'000)	**2016** ($'000)	**2017** ($'000)
Dr McNamara, Higher Representation Theory ARC, DE15	Yes	R	DE150101415			134	134	134

PART I - Statements on Progress (DE150101415)

I1. For each participant on this Proposal, please attach a statement detailing progress for each Project/Award/Fellowship involving that participant who has been awarded funding for 2013 under the ARC Discovery Projects, Discovery Indigenous Researcher Development, Discovery Indigenous, Linkage Projects schemes or any ARC Fellowships scheme.

	Project ID	First named investigator	Scheme	Statement
1				
2				
3				

J1. Other Agencies

Have you submitted or do you intend to submit a similar Proposal to any other agency?

Other Agency Submission

No

If Yes, please select one of the following:

Other Agency Name

Not applicable for this candidate

If Other is selected above, please enter the full name of the agency:

Not applicable for this candidate