<table>
<thead>
<tr>
<th>REPORT DATE (DD-MM-YYYY)</th>
<th>REPORT TYPE</th>
<th>DATES COVERED (From - To)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-03-2016</td>
<td>Final Performance Report</td>
<td>From 27-03-2014 to 31-03-2016</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TITLE AND SUBTITLE</th>
<th>CONTRACT NUMBER</th>
<th>GRANT NUMBER</th>
<th>PROGRAM ELEMENT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>(YIP) Multilinear Computing and Multilinear Algebraic Geometry</td>
<td>FA9550-13-1-0133</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AUTHOR(S)</th>
<th>PROJECT NUMBER</th>
<th>TASK NUMBER</th>
<th>WORK UNIT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lek-Heng Lim</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</th>
<th>PERFORMING ORGANIZATION REPORT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>The University of Chicago</td>
<td>Univ of Chicago Grant Ref# FP053431</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</th>
<th>SPONSOR/MONITOR’S ACRONYM(S)</th>
<th>SPONSOR/MONITOR’S REPORT NUMBER(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFOSR/PKR2</td>
<td>AFOSR/PKR2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DISTRIBUTION/AVAILABILITY STATEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>DISTRIBUTION A: Distribution approved for public release.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SUPPLEMENTARY NOTES</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>ABSTRACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>The following report details various aspects of this project. The main narrative in Section 1 describes the highlights of the most significant achievements as well as potential future developments. The next few sections contain a list of invited talks, published papers, submitted preprints, conferences organized, and personnel supported during the performance period of this project.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SUBJECT TERMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensors, multilinearity, algebraic geometry, numerical computations, computational tractability, high-resolution weighted MRI imaging, multiarray signal processing, blind identification, multilinear PageRank, structured matrix computations</td>
</tr>
</tbody>
</table>

<p>| SECURITY CLASSIFICATION OF: |</p>
<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
<th>17. LIMITATION OF ABSTRACT</th>
<th>18. NUMBER OF PAGES</th>
<th>19a. NAME OF RESPONSIBLE PERSON</th>
<th>19b. TELEPHONE NUMBER (include area code)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lek-Heng Lim</td>
<td>773-702-4263</td>
</tr>
</tbody>
</table>
INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.
Final Performance Report

Lek-Heng Lim

March 31, 2016

Grant Title: (YIP) Multilinear Computing and Multilinear Algebraic Geometry

Number: FA9550-13-1-0133

Performance Period: March 27, 2013–March 31, 2016

1 Comprehensive summary of significant work accomplished

We will only be able to provide a highlight of selected works to avoid an unduly long report. We refer the reader to the cited papers in Sections 3 and 4 for the details. Support from this grant has been explicitly acknowledged in all the following works.

The first and second items below were reported in our 2013/14 annual report; the third and fourth item were reported in our 2014/15 annual report. However all these works have seen further developments during the later stages of our performance period. In particular, there are now several more publications that resulted from these subsequent developments.

NP-hardness of tensor problems: With his collaborator Chris Hillar of Berkeley, the PI published a landmark paper titled “Most tensor problems are NP-hard” (see [14] in Section 3) in the Journal of the ACM, the premier journal in Computer Science. The results in this paper is a validation of this project. We showed that just about every multilinear generalization of common place problems in linear algebra: linear systems, least squares, eigevlue problems, singular value problems, determinant evaluation, low-rank approximations, etc — problems that form the bedrock of scientific and engineering computing — are all intractable. The implication is that one will have to find a way around this intractability to move beyond linear algebra, substantiating what the PI had proposed.

High-resolution MRI with tensors: In another piece of work with Thomas Schultz et al. (see [4, 13] in Section 3), we showed how tensor-based techniques can be used to reconstruct, to very high-resolutions, images obtained from diffusion MRI methods.

Multilinear PageRank: With David Gleich and Yongyang Yu from Purdue, as well as Austin Benson from Stanford, we extended the celebrated PageRank algorithm to a multilinear setting in which the “random surfer” model is replaced with a more realistic “spacey random surfer.” We show that in place of a simple Markov chain, the random process behind this is the vertex reinforced random walk. This is a great example of a situation where we can
produce an approximation to a multilinear problem that makes it computationally tractable. This work has been published as [9] in Section 3 and [17] in Section 4.

**Nuclear norms of tensors:** There has been an enormous amount of interest and work purporting to extend compressive sensing/sparse recovery (for vectors) and matrix completion (for matrices) to tensors. The PI has shown that this is impossible. The reason is as follows. Compressed sensing relies crucially on the fact that the $l^1$-norm is a convex underestimator of the $\|\cdot\|_0$-norm on the $l^\infty$-norm unit ball; matrix completion relies crucially on the fact that the nuclear norm is a convex underestimator of rank on the spectral norm unit ball. The PI has shown in a paper with Pierre Comon of Grenoble (see [12] in Section 3) that the generalization of this statement is false for tensors of order 3 or higher. The PI would also like to highlight that, in more recent work with Shmuel Friedland, we have thoroughly investigated the properties of tensor nuclear norm, going far beyond [12]. This new work is available as the preprint [18] in Section 4.

**Complexity of duality:** In joint work with Shmuel Friedland of UIC, the PI showed that for any given norm ball or proper cone, weak membership in its dual ball or dual cone is polynomial-time reducible to weak membership in the given ball or cone. A consequence is that the weak membership or membership problem for a ball or cone is NP-hard if and only if the corresponding problem for the dual ball or cone is NP-hard. In a similar vein, we show that computation of the dual norm of a given norm is polynomial-time reducible to computation of the given norm. This extends to convex functions satisfying a polynomial growth condition: for such a given function, computation of its Fenchel dual/conjugate is polynomial-time reducible to computation of the given function. Hence the computation of a norm or a convex function of polynomial growth is NP-hard if and only if the computation of its dual norm or Fenchel dual is NP-hard. We discuss implications of these results on the weak membership problem for a symmetric convex body and its polar dual, the polynomial approximability of Mahler volume, and the weak membership problem for the epigraph of a convex function with polynomial growth and that of its Fenchel dual. This paper has been submitted and is available as a preprint (see [19] in Section 4).

**Semialgebraic geometry of nonnegative tensor rank:** This is joint work with Yang Qi, a postdoctoral scholar jointly supervised by Pierre Comon and the PI. We study the semialgebraic structure of $D_r$, the set of nonnegative tensors of nonnegative rank not more than $r$, and use the results to infer various properties of nonnegative tensor rank. We determine all nonnegative typical ranks for cubical nonnegative tensors and show that the direct sum conjecture is true for nonnegative tensor rank. Under some mild condition (non-defectivity), we show that nonnegative, real, and complex ranks are all equal for a general nonnegative tensor of nonnegative rank strictly less than the complex generic rank. In addition, such nonnegative tensors always have unique nonnegative rank-$r$ decompositions if the real tensor space is $r$-identifiable. We determine conditions under which a best nonnegative rank-$r$ approximation has a unique nonnegative rank-$r$ decomposition: for $r \leq 3$, this is always the case; for general $r$, this is the case when the best nonnegative rank-$r$ approximation does not lie on the boundary of $D_r$. This work has been published as [6] but builds on our earlier work [8] in Section 3.
As is often the case in research work, the pursuit of the original goals could lead to unanticipated developments. There have been two lines of such developments that evolved naturally from the work in this project. Both developments are in-line with the scope of our original proposal but it will require significant further investments (in terms of time, energy, and funding) to develop them further — the PI plans to apply again to AFOSR as well as other funding agencies to support the following works but would like to report some initial findings in the next two subsections.

1.1 Distances between subspaces of different dimensions

The study of Grassmann varieties (described in Section 4 of our original proposal) have led to the following development: The Grassmann variety paramaterizes all linear subspaces of a given dimension in an ambient space. A distance measure on this variety naturally gives rise to a distance between any two linear subspaces of the same dimension. What about linear subspaces of different dimensions? We have discovered a notion of distance based on Schubert varieties that allows us to extend any distance measure for linear subspaces of the same dimension to linear subspaces of different dimensions. Furthermore such distances can be computed stably and efficiently in polynomial-time. This has been described in the paper [5] in Section 3.

There is more: The next stage of this work involves Dr. Ke Ye, the PI’s postdoc working on this project and Ken Sze-Wai Wong, the PI’s PhD student (see Section 6). This next stage is firstly an extension of the above to affine subspaces of different dimensions. But while developing the idea, we realized that the affine Grassmannian – the analogue of the Grassmann variety for affine subspaces — is relatively unstudied and we have decided to lay the foundations for this object (defining distances, probability densities, developing optimization algorithms, and studying other basic properties, etc). We expect the affine Grassmannian to be important in practical engineering applications. One reason is that we found out that many statistical estimation problems (linear regression, errors-in-variables regression, principal components analysis, support vector machines, etc) can be formulated as optimization problems over the affine Grassmannian. This is described in detail in the preprint [20] in Section 4.

1.2 Fastest algorithms for structured matrix computations

The study of tensor rank and tensor decompositions (described in Section 5.2 of our original proposal) have led to the following development: While finding interesting tensors to investigate, we realized that an important class of tensors are the “structure tensors” of common bilinear operations in numerical computing. Decompositions of such tensors give us explicit algorithms to compute such bilinear operations. Our initial study has now appeared in the papers [1, 3] in Section 3, where we determine the tensor rank decompositions of many structure tensors arising from the most common bilinear operations in use, particularly for the structured matrix-vector products with various structured matrices (Toeplitz, Hankel, circulant, Toeplitz-plus-Hankel, BTTB, banded, symmetric, etc). The next step of this work is to translate all these decompositions into actual algorithms that can be readily used by practitioners. By what we have shown, these algorithms will be the fastest possible in terms of bilinear complexity.
2 Invited talks during performance period

The PI gave the following invited talks during the performance period. This grant is explicitly acknowledged in the slides used for the presentations.


- “Structured matrix computations via tensor decompositions,” Workshop in Low-Rank Optimization Techniques, Hausdorff Center for Mathematics, Bonn, Germany, June 8–12, 2015.


• “Factoring arbitrary matrices into product of structured matrices,” Structured Matrices and Tensors: Analysis, Algorithms and Applications, National Taiwan University, Taipei, Taiwan, December 8–11, 2014.

• “Distances between subspaces of different dimensions,” Scientific Computing and Matrix Computations Seminar, University of California, Berkeley, CA, November 19, 2014.


• “Learning subspaces of different dimensions,” Workshop on Mathematical Issues in Information Sciences, Xi’an, China, July 5–10, 2014.

• “Blind multilinear identification,” Department of Mathematics, Tsinghua University, Beijing, China, June 19, 2014.


• “Hypermatrices,” Mathematics Colloquium, Department of Mathematics, University of Wisconsin, Madison, WI, May 2, 2014.

• “Hypermatrices,” Mathematics Colloquium, Department of Mathematics, University of Illinois, Urbana-Champaign, IL, April 24, 2014.

• “Learning subspaces of different dimensions,” Statistics Colloquium, Department of Statistics, Pennsylvania State University, University Park, PA, April 17, 2014.

• “Hypermatrices,” Colloquium, Department of Mathematics and Statistics, McMaster University, Hamilton, ON, April 4, 2014.


• “The role of tensors in numerical mathematics,” Peaceman Lecture, Department of Computational and Applied Mathematics, Rice University, Houston, TX, January 27, 2014.

• “Hodge decomposition in data analysis,” AMS Short Course on Geometry and Topology in Statistical Inference, Joint Mathematics Meetings, Baltimore, MD, January 13, 2014.

• “Numerical linear algebra for subspace learning,” TIMS Winter School for Scientific Computing, Taida Institute of Mathematical Sciences, National Taiwan University, Taipei, Taiwan, December 5, 2013.

• “Tensors and hypermatrices,” Mathematics Colloquium, Department of Mathematics, University of Alabama, Birmingham, AL, September 27, 2013.


• “Lectures on tensors and hypermatrices,” (4 lectures), Centro de Estruturas Lineares e Combinatórias, University of Lisbon, Lisbon, Portugal, July 22–26, 2013.

• “Algebraic geometry of matrices,” (4 lectures), Advanced School and Workshop on Matrix Geometries and Applications, Abdus Salam International Centre for Theoretical Physics, Trieste, Italy, July 1–12, 2013.

• “Tensors and hypermatrices,” 100th Anniversary of the School of Mathematics: Young Mathematician Forum, Peking University, Beijing, China, June 18–21, 2013.

• “Multiplying higher-order tensors,” Session on Multilinear Algebra and Tensor Decompositions, 18th ILAS Conference, Providence, RI, June 3–7, 2013.


• “Hypermatrices,” Departmental Colloquium, Department of Mathematics, University of Illinois, Chicago, IL, April 26, 2013.

• “Hypermatrices,” Center for Computational and Applied Mathematics Seminar, Department of Mathematics, Purdue University, West Lafayette, IN, April 5, 2013.

3 Publications during performance period

The PI published the following papers during this period. This grant is explicitly acknowledged in all of them.


4 Preprints submitted

The following preprints contain work done during this period. This grant is explicitly acknowledged in all of them.


5 Conference organized during performance period

The PI organized the following professional meetings in part to seek interactions and potential collaborations on various aspects of the work related to this project.

• 2015 STEVANOVICH CENTER CONFERENCES: Conference on Geometry and Data Analysis, University of Chicago, IL, Jun 8–10, 2015 (with S. Weinberger), http://stevanovichcenter.uchicago.edu/page/conference-geometry-and-data-analysis

• 2014 SIMONS INSTITUTE WORKSHOP: Workshop on Tensors in Computer Science and Geometry, University of California, Berkeley, CA, Fall 2014 (with H. Cohn, J. Morton, G. Ottaviani), http://simons.berkeley.edu/workshop_alggeometry3.html


6 Personnel involved

The following is a list of all personnel who have worked with the PI during the performance period of this project. Their involvements with the project range from tangential to substantial. Two postdoctoral scholars Shenglong Hu and Ke Ye were each funded for a few months by this grant. A few others had received some amount of travel support or computing equipment paid for from this grant. The remaining personnel were not directly supported from this grant but benefited in indirect ways like working under the PI’s supervision during summer months (when the PI is paid summer salary from this grant).

6.1 Postdocs

• **SHENGLONG HU**, Postdoctoral Scholar, 2015–2016, now Associate Professor in Mathematics at Tianjin University

• **YANG QI**, Postdoctoral Scholar, joint with Pierre Comon, since 2013

• **JOSE RODRIGUEZ**, NSF Postdoctoral Fellow and Provost’s Postdoctoral Scholar since 2015, winner of 2016 Provost’s Career Enhancement Postdoctoral Scholarship

• **ANNE SHIU**, Dickson Instructor and NSF Postdoctoral Fellow, joint with Mathias Drton, 2011–2014, now Assistant Professor in Mathematics at Texas A&M University

DISTRIBUTION A: Distribution approved for public release.
• KE YE, Dickson Instructor and Postdoctoral Scholar, since 2012

6.2 PhD Students
• GREGORY NAITZAT, Department of Statistics, since 2015
• KATHERINE TURNER, Department of Mathematics, joint with Shmuel Weinberger, 2010–2015, winner of Nadine Kowalsky Prize, now Postdoc in Statistics at EPFL
• KEN SZE-WAI WONG, Department of Statistics, since 2012
• LIWEN ZHANG, Department of Computer Science, since 2011

6.3 MS Students
• FREDDY BOULTON, Department of Statistics, 2015–2016, undergraduate in BS/MS program
• LIJUN DING, Department of Statistics, 2014–2016, now PhD student in Operations Research and Industrial Engineering, Cornell University
• BYOL KIM, Department of Statistics, 2013–2015, now PhD student in Statistics, University of Chicago
• SHAN LU, Department of Statistics, joint with Sou-Cheng Choi, since 2015
• JOHN SANTERRE, Department of Computer Science, 2012–2014, now PhD student in Computer Science, University of Chicago

7 Thanks
The PI would like to express his sincere gratitude to AFOSR and his program managers for their kind support. This award has been instrumental in furthering not just the PI’s career but also those of many junior personnel involved (see Section 6). Thank you very much for this opportunity.
1.

1. Report Type
Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.
lekheng@galton.uchicago.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report
650-387-6896

Organization / Institution name
University of Chicago

Grant/Contract Title
The full title of the funded effort.
Multilinear Computing and Multilinear Algebraic Geometry

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".
FA9550-13-1-0133

Principal Investigator Name
The full name of the principal investigator on the grant or contract.
Lek-Heng Lim

Program Manager
The AFOSR Program Manager currently assigned to the award
Doug Riecken

Reporting Period Start Date
03/27/2013

Reporting Period End Date
03/31/2016

Abstract
With Shmuel Friedland of UIC, we proved in [19] that a norm is NP-hard to compute iff its dual norm is NP-hard to compute, and extended such computational equivalence to a number of dual objects commonly occurring in optimization. In [18] we showed how one may naturally extend the matrix nuclear norm to higher-order tensors and view it as a continuous variant of tensor rank. We established several surprising properties: tensor nuclear norm depends on the choice of base field (like tensor rank), is upper semicontinuous (unlike tensor rank), satisfies the Comon's conjecture (unknown for tensor rank), and is NP-hard to compute (applying the result in [19]).

In joint work with Pierre Comon and the PI's postdoc Yang Qi, we investigated a long list of properties of nonnegative tensor rank that is, in our view, as exhaustive as current technologies allow. See [6, 8] for more information.

Distribution Statement
This is block 12 on the SF298 form.
Distribution A - Approved for Public Release

Explanation for Distribution Statement
DISTRIBUTION A: Distribution approved for public release.
If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form
Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF
The maximum file size for an SF298 is 50MB.

AFD-070820-035-Lim.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF. The maximum file size for the Report Document is 50MB.

final2016.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:


DISTRIBUTION A: Distribution approved for public release.


2. New discoveries, inventions, or patent disclosures:
Do you have any discoveries, inventions, or patent disclosures to report for this period?

No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

<table>
<thead>
<tr>
<th></th>
<th>Starting FY</th>
<th>FY+1</th>
<th>FY+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment/Facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supplies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Jul 11, 2016 02:40:23 Success: Email Sent to: lekheng@galton.uchicago.edu

DISTRIBUTION A: Distribution approved for public release.