
VOLUME 19 NUMBER 2



APRIL 2006

JOURNAL

OF THE

AMERICAN MATHEMATICAL SOCIETY

EDITORS

Ingrid Daubechies
Robert Lazarsfeld
John W. Morgan
Andrei Okounkov
Terence Tao

ASSOCIATE EDITORS

Francis Bonahon
Robert L. Bryant
Weinan E
Pavel I. Etingof
Mark Goresky
Michael J. Hopkins
Alexander S. Kechris
Tomasz S. Mrowka
Andrew M. Odlyzko
Bjorn Poonen
Victor S. Reiner
Jonathan M. Rosenberg
Oded Schramm
Karen E. Smith
Richard L. Taylor
S. R. S. Varadhan
Lai-Sang Young
Shou-Wu Zhang

PROVIDENCE, RHODE ISLAND USA

ISSN 0894-0347

Available electronically at
www.ams.org/jams/

Journal of the American Mathematical Society

This journal is devoted to research articles of the highest quality in all areas of pure and applied mathematics.

Submission information. See **Information for Authors** at the end of this issue.

Publisher Item Identifier. The Publisher Item Identifier (PII) appears at the top of the first page of each article published in this journal. This alphanumeric string of characters uniquely identifies each article and can be used for future cataloging, searching, and electronic retrieval.

Postings to the AMS website. Articles are posted to the AMS website individually after proof is returned from authors and before appearing in an issue.

Subscription information. The *Journal of the American Mathematical Society* is published quarterly. Beginning January 1996 the *Journal of the American Mathematical Society* is accessible from www.ams.org/journals/. Subscription prices for Volume 19 (2006) are as follows: for paper delivery, US\$276 list, US\$221 institutional member, US\$248 corporate member, US\$166 individual member; for electronic delivery, US\$248 list, US\$198 institutional member, US\$223 corporate member, US\$149 individual member. Upon request, subscribers to paper delivery of this journal are also entitled to receive electronic delivery. If ordering the paper version, add US\$11 for surface delivery outside the United States and India; US\$18 to India. Expedited delivery to destinations in North America is US\$17; elsewhere US\$40. For paper delivery a late charge of 10% of the subscription price will be imposed upon orders received from nonmembers after January 1 of the subscription year.

Back number information. For back issues see www.ams.org/bookstore.

Subscriptions and orders should be addressed to the American Mathematical Society, P.O. Box 845904, Boston, MA 02284-5904 USA. *All orders must be accompanied by payment.* Other correspondence should be addressed to 201 Charles Street, Providence, RI 02904-2294 USA.

Copying and reprinting. Material in this journal may be reproduced by any means for educational and scientific purposes without fee or permission with the exception of reproduction by services that collect fees for delivery of documents and provided that the customary acknowledgment of the source is given. This consent does not extend to other kinds of copying for general distribution, for advertising or promotional purposes, or for resale. Requests for permission for commercial use of material should be addressed to the Acquisitions Department, American Mathematical Society, 201 Charles Street, Providence, RI 02904-2294 USA. Requests can also be made by e-mail to reprint-permission@ams.org.

Excluded from these provisions is material in articles for which the author holds copyright. In such cases, requests for permission to use or reprint should be addressed directly to the author(s). (Copyright ownership is indicated in the notice in the lower right-hand corner of the first page of each article.)

The *Journal of the American Mathematical Society* is published quarterly by the American Mathematical Society at 201 Charles Street, Providence, RI 02904-2294 USA and is mailed from Providence, Rhode Island. Periodicals postage is paid at Providence, Rhode Island. Postmaster: Send address changes to Journal of the AMS, American Mathematical Society, 201 Charles Street, Providence, RI 02904-2294 USA.

© 2006 by the American Mathematical Society. All rights reserved.

This journal is indexed in *Mathematical Reviews*, *Zentralblatt MATH*, *Science Citation Index*[®], *Science Citation Index*^{™-Expanded}, *ISI Alerting Services*SM, *CompuMath Citation Index*[®], and *Current Contents*[®]/*Physical, Chemical & Earth Sciences*.

Printed in the United States of America.

⊗ The paper used in this journal is acid-free and falls within the guidelines established to ensure permanence and durability.

10 9 8 7 6 5 4 3 2 1 11 10 09 08 07 06

JOURNAL OF THE AMERICAN MATHEMATICAL SOCIETY
CONTENTS

Vol. 19, No. 2

April 2006

| | |
|---|-----|
| A. J. Berrick, F. R. Cohen, Y. L. Wong, and J. Wu, Configurations, braids, and homotopy groups | 265 |
| Martin Möller, Variations of Hodge structures of a Teichmüller curve ... | 327 |
| Niels Lauritzen, Ulf Raben-Pedersen, and Jesper Funch Thomsen, Global F-regularity of Schubert varieties with applications to \mathcal{D}-modules | 345 |
| Alexandru D. Ionescu and Stephen Wainger, L^p boundedness of discrete singular Radon transforms | 357 |
| Danny Calegari and David Gabai, Shrinkwrapping and the taming of hyperbolic 3-manifolds | 385 |
| J. M. Landsberg, The border rank of the multiplication of 2×2 matrices is seven | 447 |
| Dev P. Sinha, Operads and knot spaces | 461 |
| Jeff Cheeger and Gang Tian, Curvature and injectivity radius estimates for Einstein 4-manifolds | 487 |

Editors

Ingrid Daubechies
Department of Mathematics & PACM
218 Fine Hall
Princeton University
Princeton, NJ 08544-1000 USA
ingrid@math.princeton.edu

Robert Lazarsfeld
Department of Mathematics
University of Michigan
Ann Arbor, MI 48109-1109 USA
rlaz@umich.edu

John W. Morgan
Department of Mathematics
Columbia University
2990 Broadway
New York, NY 10027-0029 USA
jm@math.columbia.edu

Andrei Okounkov
Department of Mathematics
Fine Hall
Princeton University
Princeton, NJ 08544 USA
okounkov@princeton.edu

Terence Tao
Department of Mathematics
University of California, Los Angeles
405 Hilgard Avenue
Los Angeles, CA 90095-1555 USA
tao@math.ucla.edu

Associate Editors

Francis Bonahon, University of Southern California
Robert L. Bryant, Duke University
Weinan E, Princeton University
Pavel I. Etingof, Massachusetts Institute of Technology
Mark Goresky, Institute for Advanced Study, Princeton
Michael J. Hopkins, Massachusetts Institute of Technology
Alexander S. Kechris, California Institute of Technology
Tomasz S. Mrowka, Massachusetts Institute of Technology
Andrew M. Odlyzko, University of Minnesota
Bjorn Poonen, University of California, Berkeley
Victor S. Reiner, University of Minnesota, Minneapolis
Jonathan M. Rosenberg, University of Maryland
Oded Schramm, Microsoft Research
Karen E. Smith, University of Michigan
Richard L. Taylor, Harvard University
S. R. S. Varadhan, New York University–Courant Institute
Lai-Sang Young, New York University–Courant Institute
Shou-Wu Zhang, Columbia University

Assistant to the Editorial Board

Cheryl A. Cantore
Princeton University
133 East Pyne
Princeton, NJ 08544 USA
cheryl@princeton.edu

Editorial Information

Information on the backlog for this journal can be found on the AMS website starting from <http://www.ams.org/jams>.

In an effort to make articles available as quickly as possible, articles are posted to the AMS website individually after proof is returned from authors and before appearing in an issue.

A Consent to Publish and Copyright Agreement is required before a paper will be published in this journal. After a paper is accepted for publication, the Providence office will send a Consent to Publish and Copyright Agreement to all authors of the paper. By submitting a paper to this journal, authors certify that the manuscript has not been submitted to nor is it under consideration for publication by another journal, conference proceedings, or similar publication.

Information for Authors

Initial submission. Two copies of the paper should be sent directly to one of the Editors (not an Associate Editor), and the author should keep one copy.

IF an editor is agreeable, an electronic manuscript prepared in $\text{T}_{\text{E}}\text{X}$ or $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ may be submitted by pointing to an appropriate URL on a preprint or e-print server.

The first page must contain a *descriptive title* that is short, but informative; useless or vague phrases such as “some remarks about” or “concerning” should be avoided. Although an abstract is not required upon initial submission, upon acceptance authors will be requested to supply an abstract for the electronic version of this journal. The AMS offers free worldwide access to the electronic abstracts. An abstract should be at least one complete sentence and at most 300 words. No abstracts will appear in the printed journal starting in 1998. Included with the footnotes to the paper should be the 2000 *Mathematics Subject Classification* representing the primary and secondary subjects of the article. The classifications are accessible from www.ams.org/msc/. The list of classifications is also available in print starting with the 1999 annual index of *Mathematical Reviews*. The Mathematics Subject Classification footnote may be followed by a list of *key words and phrases* describing the subject matter of the article and taken from it. Journal abbreviations used in bibliographies are listed in the latest *Mathematical Reviews* annual index. The series abbreviations are also accessible from www.ams.org/publications/. To help in preparing and verifying references, the AMS offers MR Lookup, a Reference Tool for Linking, at www.ams.org/mrlookup/. When the manuscript is submitted, authors should supply the editor with electronic addresses if available. These will be printed after the postal address at the end of each article.

Electronically prepared manuscripts. The AMS encourages electronically prepared manuscripts, with a strong preference for $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$. To this end, the Society has prepared $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ author packages for each AMS publication. Author packages include instructions for preparing electronic manuscripts, the *AMS Author Handbook*, samples, and a style file that generates the particular design specifications of that publication series. Articles properly prepared using the $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ style file and the `\label` and `\ref` commands automatically enable extensive intra-document linking to the bibliography and other elements of the article for searching electronically on the Web. Because linking must often be added manually to electronically prepared manuscripts in other forms of $\text{T}_{\text{E}}\text{X}$, using $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ also reduces the amount of technical intervention once the files are received by the AMS. This results in fewer errors in processing and saves the author proofreading time. $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ papers also move more efficiently through the production stream, helping to minimize publishing costs.

$\mathcal{A}\mathcal{M}\mathcal{S}$ - $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ is the highly preferred format of $\text{T}_{\text{E}}\text{X}$, but author packages are also available in $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\text{T}_{\text{E}}\text{X}$. Those authors who make use of these style files from the beginning of the writing process will further reduce their own efforts. Manuscripts prepared electronically in $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ or plain $\text{T}_{\text{E}}\text{X}$ are normally not acceptable due to the high amount of technical time required to insure that the file will run properly through the AMS in-house production system. $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ users will find that $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ is the same as $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ with additional commands to simplify the typesetting of mathematics, and users of plain $\text{T}_{\text{E}}\text{X}$ should have the foundation for learning $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$.

Authors may retrieve an author package from the AMS website starting from www.ams.org/tex/ or via FTP to [ftp.ams.org](ftp://ftp.ams.org) (login as `anonymous`, enter username as password, and type `cd pub/author-info`). The *AMS Author Handbook* and the *Instruction Manual* are available in PDF format following the author packages link from

www.ams.org/tex/. The author package can also be obtained free of charge by sending email to pub@ams.org (Internet) or from the Publication Division, American Mathematical Society, 201 Charles Street, Providence, RI 02904-2294 USA. When requesting an author package, please specify $\mathcal{A}\mathcal{M}\mathcal{S}\text{-}\mathcal{L}\mathcal{A}\mathcal{T}\mathcal{E}\mathcal{X}$ or $\mathcal{A}\mathcal{M}\mathcal{S}\text{-}\mathcal{T}\mathcal{E}\mathcal{X}$, Macintosh or IBM (3.5) format, and the publication in which your paper will appear. Please be sure to include your complete mailing address.

At the time of submission, authors should indicate if the paper has been prepared using $\mathcal{A}\mathcal{M}\mathcal{S}\text{-}\mathcal{L}\mathcal{A}\mathcal{T}\mathcal{E}\mathcal{X}$ or $\mathcal{A}\mathcal{M}\mathcal{S}\text{-}\mathcal{T}\mathcal{E}\mathcal{X}$ and provide the Editor with a paper manuscript that matches the electronic manuscript. The final version of the electronic manuscript should be sent to the Providence office immediately after the paper has been accepted for publication. The author should also send the final version of the paper manuscript to the Editor, who will forward a copy to the Providence office. Editors will require authors to send their electronically prepared manuscripts to the Providence office in a timely fashion. Electronically prepared manuscripts can be submitted via the Web at www.ams.org/submit-book-journal/, sent via email to pub-submit@ams.org (Internet), or sent on diskette to the Electronic Prepress Department, American Mathematical Society, 201 Charles Street, Providence, RI 02904-2294 USA. When sending a manuscript electronically via email or diskette, please be sure to include a message indicating in which publication the paper has been accepted. No corrections will be accepted electronically. Authors must mark their changes on their proof copies and return them to the Providence office. Complete instructions on how to send files are included in the author package.

Electronic graphics. Comprehensive instructions on preparing graphics are available from www.ams.org/jourhtml/authors.html. A few of the major requirements are given here.

Submit files for graphics as EPS (Encapsulated PostScript) files. This includes graphics originated via a graphics application as well as scanned photographs or other computer-generated images. If this is not possible, TIFF files are acceptable as long as they can be opened in Adobe Photoshop or Illustrator. No matter what method was used to produce the graphic, it is necessary to provide a paper copy to the AMS.

Authors using graphics packages for the creation of electronic art should also avoid the use of any lines thinner than 0.5 points in width. Many graphics packages allow the user to specify a “hairline” for a very thin line. Hairlines often look acceptable when proofed on a typical laser printer. However, when produced on a high-resolution laser imagesetter, hairlines become nearly invisible and will be lost entirely in the final printing process.

Screens should be set to values between 15% and 85%. Screens which fall outside of this range are too light or too dark to print correctly. Variations of screens within a graphic should be no less than 10%.

AMS policy on making changes to articles after posting. Articles are posted to the AMS website individually after proof is returned from authors and before appearing in an issue. To preserve the integrity of electronically published articles, once an article is individually posted to the AMS website but not yet in an issue, changes cannot be made in place in the paper. However, an “Added after posting” section may be added to the paper right before the References when there is a critical error in the content of the paper. The “Added after posting” section gives the author an opportunity to correct this type of critical error before the article is put into an issue for printing and before it is then reposted with the issue. The “Added after posting” section remains a permanent part of the paper. The AMS does not keep author-related information, such as affiliation, current address, and email address, up to date after a paper is initially posted.

Once the article is assigned to an issue, even if the issue has not yet been posted to the AMS website corrections may be made to the paper by submitting a traditional errata article to the Editor. The errata article will appear in a future print issue and will link back and forth on the Web to the original article online.

Secure manuscript tracking on the Web and via email. Authors can track their manuscripts through the AMS journal production process using the personal AMS ID and

Article ID printed in the upper right-hand corner of the Consent to Publish form sent to each author who publishes in AMS journals. Access to the tracking system is available from www.ams.org/mstrack/ or via email sent to mstrack-query@ams.org. To access by email, on the subject line of the message simply enter the AMS ID and Article ID. To track more than one manuscript by email, choose one of the Article IDs and enter the AMS ID and the Article ID followed by the word *all* on the subject line. An explanation of each production step is provided on the Web through links from the manuscript tracking screen. Questions can be sent to jams-query@ams.org.

T_EX files available. Beginning with the January 1992 issue of the *Bulletin* and the January 1996 issues of *Transactions*, *Proceedings*, *Mathematics of Computation*, and the *Journal of the AMS*, T_EX files can be downloaded from the AMS website starting from www.ams.org/journals/. Authors without Web access may request their files at the address given below after the article has been published. For *Bulletin* papers published in 1987 through 1991 and for *Transactions*, *Proceedings*, *Mathematics of Computation*, and the *Journal of the AMS* papers published in 1987 through 1995, T_EX files are available upon request for authors without Web access by sending email to file-request@ams.org or by contacting the Electronic Prepress Department, American Mathematical Society, 201 Charles Street, Providence, RI 02904-2294 USA. The request should include the title of the paper, the name(s) of the author(s), the name of the publication in which the paper has or will appear, and the volume and issue numbers if known. The T_EX file will be sent to the author making the request after the article goes to the printer. If the requestor can receive Internet email, please include the email address to which the file should be sent. Otherwise please indicate a diskette format and postal address to which a disk should be mailed. **Note:** Because T_EX production at the AMS sometimes requires extra fonts and macros that are not yet publicly available, T_EX files cannot be guaranteed to run through the author's version of T_EX without errors. The AMS regrets that it cannot provide support to eliminate such errors in the author's T_EX environment.

Inquiries. Any inquiries concerning a paper that has been accepted for publication that cannot be answered via the manuscript tracking system mentioned above should be sent to jams-query@ams.org or directly to the Electronic Prepress Department, American Mathematical Society, 201 Charles Street, Providence, RI 02904-2294 USA.

JOURNAL OF THE AMERICAN MATHEMATICAL SOCIETY
CONTENTS

Vol. 19, No. 2

April 2006

| | |
|---|-----|
| A. J. Berrick, F. R. Cohen, Y. L. Wong, and J. Wu , Configurations, braids, and homotopy groups | 265 |
| Martin Möller , Variations of Hodge structures of a Teichmüller curve ... | 327 |
| Niels Lauritzen, Ulf Raben-Pedersen, and Jesper Funch Thomsen , Global F -regularity of Schubert varieties with applications to \mathcal{D} -modules | 345 |
| Alexandru D. Ionescu and Stephen Wainger , L^p boundedness of discrete singular Radon transforms | 357 |
| Danny Calegari and David Gabai , Shrinkwrapping and the taming of hyperbolic 3-manifolds | 385 |
| J. M. Landsberg , The border rank of the multiplication of 2×2 matrices is seven | 447 |
| Dev P. Sinha , Operads and knot spaces | 461 |
| Jeff Cheeger and Gang Tian , Curvature and injectivity radius estimates for Einstein 4-manifolds | 487 |

Journal of the American Mathematical Society

VOLUME 19

NUMBER 2

PAGES 265–526

APRIL 2006



0894-0347(200604)19:2;1-B