Kevin Carlberg

My research combines machine learning with modeling and simulation.
The goal: discover structure in massive simulation data and drastically reduce simulation costs.

Research interests

Reduced-order modeling, Machine learning, High-performance computing, Multiphysics simulations, Bayesian inference, Uncertainty quantification, Mathematical optimization, Surrogate modeling, Iterative solvers for sparse linear systems, Computational fluid dynamics, Finite element analysis

Education

2006–2011 **Ph.D., Aeronautics & Astronautics**, *Stanford University*.
Ph.D. Minor: Computational and Mathematical Engineering
Research Adviser: Dr. Charbel Farhat
Dissertation: "Model Reduction of Nonlinear Mechanical Systems via Optimal Projection and Tensor Approximation"
GPA: 4.15/4.0

2005–2006 **M.S., Aeronautics & Astronautics**, *Stanford University*.
GPA: 4.21/4.0
ranked 1st in class

2001–2005 **B.S., Mechanical Engineering**, *Washington University in St. Louis*.
GPA: 4.0/4.0
summa cum laude
Valedictorian

Highlights

- 13 papers, including one of the 'top ten most cited International Journal for Numerical Methods in Engineering papers of 2011.'
- 10 invited talks, including at MIT, UC Berkeley, Cornell, and Stanford University; 11 conference talks.
- 3 research fellowships, including the President Harry S. Truman Fellowship in National Security Science and Engineering (research budget: $260k/3 years).
- Directly supervised 2 postdocs and 4 PhD candidates.
- Ranked first in:
  - Stanford University Aeronautics & Astronautics PhD qualifying exams (2006)
  - Stanford University Aeronautics & Astronautics M.S. Class of 2006
  - Washington University School of Engineering & Applied Science B.S. Class of 2005

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Truman Fellow, Sandia National Laboratories

Research experience (selected)

Sandia National Laboratories, *Truman Fellow*, Quantitative Modeling & Analysis Dept, Livermore, CA.

Dec 2013–present **Data assimilation via Bayesian inversion and model reduction**.
- Developing methods to integrate experimental data with computational models. To achieve this, we are combining importance sampling with reduced-order models equipped with uncertainty-quantification metrics.
- *Collaborators*: Matthias Morzfeld, Fei Lu, Alexandre Chorin (UC Berkeley)

May 2014–present **Model-reduction-enabled Krylov-subspace recycling for sparse linear systems**.
- Developing methods to integrate model-reduction techniques for optimal, goal-oriented truncation with recycling Krylov subspaces in the context of sequences of sparse linear systems.
- *Collaborators*: Virginia Forstall, Paul Tsuji, Ray Tuminaro

Jan 2014–Apr 2014 **Adaptive *a posteriori* refinement of reduced-order models**.
- Developed a novel methodology to refine *a posteriori* reduced-order models via an analogue to mesh-adaptive h-refinement.
- On a hyperbolic problem, the method allowed reduced-order models to capture phenomena not present in training data and satisfy any prescribed error tolerance.
- Associated publication: [2]

May 2013–present **Model reduction for quantum-mechanical systems**.
- Developing a method to preserve structure for quantum-mechanical systems to enable real-time control in quantum computing.
- *Collaborator*: Mohan Sarovar

Nov 2012–May 2014 **Uncertainty quantification for reduced-order models**.
- Developed a statistics-based approach to quantify the uncertainty introduced by the use of a reduced-order model *in lieu* of the full-order computational model.
- Method exploits physics-based error indicators, e.g., error bounds and dual-norm residuals.
- Associated publication: [1]
- *Collaborator*: Martin Drohmann

Mar 2012–present **Model reduction for compressible cavity flows**.
- Applied GNAT [5] and implementation in AERO-F to a compressible Navier–Stokes simulation (with DES turbulence model) of a cavity-flow problem with over 1.2 million degrees of freedom.
- Reduced simulation times from 48 cpu $\times$ 5 hours to 2 cpu $\times$ 31 min (232x savings factor).
- *Collaborators*: Matthew Barone, Srini Arunajatesan

Mar 2012–Oct 2013 **A Trilinos-based module for nonlinear model reduction**.
- Developed a model-reduction interface to equip Trilinos-based simulation codes for nonlinear model reduction.
- Significantly decreased the barrier to entry for implementing model-reduction methods in different Trilinos-based codes.
- *Collaborators*: Julien Cortial (project lead), Andy Salinger

Dec 2011–present **Decrease the temporal complexity for nonlinear reduced-order models**.
- Developed a technique that exploits time-domain data to accurately forecast the solution at future time steps. The Newton solver employs this forecast as an initial guess.
- Decreased computational times by a factor of two with no loss in accuracy for reduced-order models of a finite-element truss structure model.
- Associated publication: [4]
- *Collaborators*: Jaideep Ray, Bart van Bloemen Waanders

Dec 2011–Jan 2014 **Preserve classical Lagrangian/Hamiltonian structure in nonlinear model reduction**.

- Developed a model-reduction method that preserves Lagrangian structure—which associates with critical properties such as energy conservation and symplectic time-evolution maps—and leads to efficiency in the presence of high-order nonlinearities.
- Demonstrated greatly improved accuracy and stability over existing model-reduction methods on a geometrically nonlinear structural-dynamics problem.
- Associated publications: [3, 9]
- *Collaborators*: Ray Tuminaro, Paul Boggs

Stanford University, *Research Assistant*, Farhat Research Group, Stanford, CA.

2008–2011 **Fast-turnaround design of Toyota Formula One cars using reduced-order models**.

- Developed the GNAT model-reduction technique that uses data reconstruction to accelerate large-scale nonlinear simulations. Achieved speedups over 100x with errors less than 5% on structure, fluid, electronic, and neuron models.
- Devised a model reduction method that decreases the cost of nonlinear simulations via a quasi-Newton approach. Obtained speedups around 7x with errors below 5% on car aerodynamics problems.
- Implemented these methods in AERO-F: a massively parallel, compressible, Navier-Stokes finite-volume solver.
- Associated publications: [5, 7, 10]
- *Collaborators*: Charbel Farhat, Charbel Bou-Mosleh, David Amsallem, Julien Cortial

2007–2009 **Efficient PDE-constrained optimization**.

- Developed an iterative solver that uses model-reduction concepts to accelerate solving sequences of sparse linear systems that arise in PDE-constrained optimization. Achieved speedups over 7x on V-22 Osprey wing panel model.
- Implemented this solver in the group's domain decomposition-based structural mechanics finite element code.
- Devised a low-cost, goal-oriented model reduction method for steady-state systems. Improved both efficiency and accuracy compared with standard model reduction methods on a large-scale aeroelastic research wing model.
- Associated publications: [6, 12, 13]
- *Collaborators*: Charbel Farhat

Buerge Engineering Corporation, *Aerodynamics researcher*, St. Louis, Missouri

2003–2005 **Active flow control experimentation**.

- Devised and conducted wind-tunnel experiments to analyze the effect of surface blowing as a form of active flow control on the aerodynamic performance of a cylinder. Obtained lift-to-drag ratios exceeding 1.2.
- Designed and built an economical, induced-flow, open test-section wind tunnel.

Engineering Software Research and Development, Inc., *Engineering intern*, St. Louis, Missouri

2003–2005 **Contact capability in finite-element software**.

- Assisted implementing contact capability into StressCheck, a commercial finite element analysis software package.
- *Collaborators* Barna Szabo, Ricardo Actis

Teaching and research advising

Instructor and Curriculum Developer

Summer 2009–10 **Introduction to Engineering Optimization**, *Army High-Performance Computing Research Center Summer Institute*, Stanford, CA.

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Teaching Assistant

Spring 2010 **Large-Scale Numerical Optimization (CME 338)**, *Stanford University*, Prof Michael Saunders.

Fall 2004, Spring 2005 **Mechanics of Deformable Bodies (ME 241)**, *Washington University in St. Louis*, Prof Barna Szabo.

Research Advising

May 2014–present **Virginia Forstall**, *PhD summer intern*, Sandia National Laboratories.
Project: Applying model reduction to Krylov-subspace iterative methods via recycling

Oct 2012–present **Martin Drohmann**, *Postdoctoral researcher*, Sandia National Laboratories.
Project: Uncertainty quantification for reduced-order models

Feb 2012–Nov 2013 **Julien Cortial**, *Postdoctoral researcher*, Sandia National Laboratories.
Project: A Trilinos-based module for nonlinear model reduction

Fall 2010 **Wade Spurlock**, *M.S. Aeronautics & Astronautics*, Stanford University.
Project: Visualizing nonlinear model reduction methods for Formula One car design

Summer 2010 **Matthew Zahr**, *B.S. Civil Engineering*, University of California, Berkeley.
Project: Comparing model reduction methods on linear and nonlinear electrical, mechanical, and biological systems. Won "best project" at AHPCRC 2010 Summer Institute.

Fall 2009 **Paul Covington**, *M.S. Computational and Mathematical Engineering*, Stanford University.
Project: Implementing shape sensitivity analysis in a massively parallel fluid code.

Honors and awards

2011–2014 **President Harry S. Truman Fellowship in National Security Science and Engineering**, *Research budget: $260k/3 years*, Sandia National Laboratories.

2008–2010 **National Science Foundation Graduate Research Fellowship**, Stanford University.

2008 **CEA-EDF-INRIA Numerical Analysis Summer School Scholarship**, Paris, France.

2007 **Nicholas J. Hoff Award**, *ranked 1st in graduating M.S. class of Aeronautics & Astronautics*, Stanford University.

2006 **Ranked 1st of 16 in Aeronautics & Astronautics Ph.D. qualifying exams**, Stanford University.

2005–2008 **National Defense Science and Engineering Graduate Fellowship**, Stanford University.

2005 **Gustav Mesmer Prize**, *ranked 1st in graduating B.S. class of Mechanical Engineering*, Washington University in St. Louis.

2001–2005 **Calvin L. Woodward Fellowship**, Washington University in St. Louis.

2001–2005 **Danforth Scholarship**, Washington University in St. Louis.

Academic service

2009–present **Journal referee**.

- *Computer Methods in Applied Mechanics and Engineering*
- *Computers and Fluids*
- *International Journal for Numerical Methods in Engineering*
- *International Journal for Numerical Methods in Fluids*
- *Journal of Computational and Applied Mechanics*
- *SIAM Journal on Optimization*
- *SIAM Journal on Scientific Computing*

2012–present **Minisymposium organizer**.

- K. Carlberg and D. Kouri, "Model-Reduction Techniques for Quantifying and Controlling Uncertainty," 2014 SIAM Conf on Uncertainty Quantification, Savannah, GA, March 31–April 3, 2014.
- K. Carlberg and M. Drohmann, "Error analysis in model reduction," 2013 SIAM Conf on Comp Sci & Eng, Boston, MA, February 25–March 1, 2013.
- D. Amsallem, K. Carlberg, and C. Farhat, "Model Order Reductions," 10th World Congress on Computational Mechanics, São Paulo, Brazil, July 8–13, 2012.
- P. Constantine and K. Carlberg, "Model reduction for nonlinear dynamical systems," 2012 SIAM Conf on Uncertainty Quantification, Raleigh, NC, April 2–5, 2012.

2011 **External examiner for postgraduate courses**, *University of Pretoria*, South Africa.

2009–2010 **Student search-committee member**, *Faculty Search Committee*, Stanford University Aeronautics & Astronautics.

2009–2011 **Seminar lead**, *Farhat Research Group Seminar Series*, Stanford University.

Journal

Recent preprints

[1] M. Drohmann and K. Carlberg. The ROMES method for statistical modeling of reduced-order-model error. *arXiv e-print*, (1405.5170), 2014.

[2] K. Carlberg. Adaptive h-refinement for reduced-order models. *arXiv e-print*, (1404.0442), 2014.

[3] K. Carlberg, R. Tuminaro, and P. Boggs. Preserving Lagrangian structure in nonlinear model reduction with application to structural dynamics. *arXiv e-print*, (1401.8044), 2014.

[4] K. Carlberg, J. Ray, and B. van Bloemen Waanders. Decreasing the temporal complexity for nonlinear, implicit reduced-order models by forecasting. *arXiv e-print*, (1209.5455), 2012.

Published

[5] K. Carlberg, C. Farhat, J. Cortial, and D. Amsallem. The GNAT method for nonlinear model reduction: effective implementation and application to computational fluid dynamics and turbulent flows. *Journal of Computational Physics*, 242:623–647, 2013.

[6] K. Carlberg and C. Farhat. A low-cost, goal-oriented 'compact proper orthogonal decomposition' basis for model reduction of static systems. *International Journal for Numerical Methods in Engineering*, 86(3):381–402, April 2011.

[7] K. Carlberg, C. Farhat, and C. Bou-Mosleh. Efficient non-linear model reduction via a least-squares Petrov–Galerkin projection and compressive tensor approximations. *International Journal for Numerical Methods in Engineering*, 86(2):155–181, April 2011. **Top ten most cited International Journal for Numerical Methods in Engineering papers of 2011**.

[8] D. Amsallem, J. Cortial, K. Carlberg, and C. Farhat. A method for interpolating on manifolds structural dynamics reduced-order models. *International Journal for Numerical Methods in Engineering*, 80(9):1241–1258, 2009.

Conference papers (refereed)

[9] K. Carlberg, R. Tuminaro, and P. Boggs. Efficient structure-preserving model reduction for nonlinear mechanical systems with application to structural dynamics. In *AIAA*

Paper 2012-1969, 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, April 23–26 2012.

[10] K. Carlberg, J. Cortial, D. Amsallem, M. Zahr, and C. Farhat. The GNAT nonlinear model reduction method and its application to fluid dynamics problems. *AIAA Paper 2011-3112, 6th AIAA Theoretical Fluid Mechanics Conference, Honolulu, HI*, June 27–30, 2011.

[11] R. Stephan and K. Carlberg. Gappy data reconstruction and applications in archaeology. In *Proceedings of the XXXVIII Annual Conference on Computer Applications and Quantitative Methods in Archaeology*, April 6–9, 2010.

[12] K. Carlberg and C. Farhat. An adaptive POD-Krylov reduced-order model for structural optimization. *8th World Congress on Structural and Multidisciplinary Optimization, Lisbon, Portugal*, June 1–5 2009.

[13] K. Carlberg and C. Farhat. A compact proper orthogonal decomposition basis for optimization-oriented reduced-order models. *AIAA Paper 2008-5964, 12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Victoria, Canada*, September 10–12, 2008.

Talks

Invited

- K. Carlberg, "Reduced-order modeling in uncertainty quantification: modeling and controlling error," Applied and Computational Math Seminar, **George Mason University**, Fairfax, VA, April 25, 2014.
- M. Drohmann and K. Carlberg, "The ROMES method for reduced-order-model uncertainty quantification: application to data assimilation," Workshop on Model Order Reduction and Data, Paris, France, January 6, 2014.
- K. Carlberg, "The GNAT method for nonlinear model reduction," Bay Area Scientific Computing Day, Lawrence Berkeley National Lab, December 11, 2013.
- K. Carlberg, "Discrete optimality and structure preservation in nonlinear model reduction," Applied Mathematics Seminar, **University of Washington**, Seattle, WA, November 21, 2013.
- K. Carlberg, "Model reduction for nonlinear fluid dynamics and structural dynamics: discrete optimality and structure preservation," Mechanical & Aerospace Engineering Colloquium, **Cornell University**, Ithaca, NY, October 8, 2013.
- K. Carlberg, "The GNAT method for model reduction of nonlinear dynamical systems," Applied Mathematics Seminar, **UC Berkeley**, Berkeley, CA, October 2, 2013.
- K. Carlberg, "The GNAT method for nonlinear model reduction: discrete optimality, practical implementation, and application to CFD," Department of Mathematics Colloquium, **Virginia Tech**, Blacksburg, VA, April 19, 2013.
- K. Carlberg, "Discrete-optimal nonlinear model reduction by the GNAT method," ACDL Seminar, **MIT**, Boston, MA, April 17, 2013.
- K. Carlberg, "The GNAT method for nonlinear model reduction: overview and perspectives on UQ application," Uncertainty Quantification Laboratory Seminar, **Stanford University**, Stanford, CA, May 3, 2012.

- K. Carlberg and C. Farhat, "The Gauss–Newton with approximated tensors (GNAT) method for nonlinear model reduction," SUPRI-B Group Seminar, **Stanford University**, Stanford, CA, June 1, 2011.
- K. Carlberg and C. Farhat, "Model reduction-based iterative methods for real-time simulation and repeated analyses of mathematical models," Linear Algebra and Optimization Seminar, **Stanford University**, Stanford, CA, October 28, 2010.

Conference

- K. Carlberg, "Adaptive h-refinement for reduced-order models with application to uncertainty control," SIAM Conference on Uncertainty Quantification, Savannah, GA, March 31–April 3, 2014.
- K. Carlberg, C. Farhat, J. Cortial, and D. Amsallem, "The GNAT nonlinear model-reduction method with application to large-scale turbulent flows," Fourth International Workshop on Model Reduction in Reacting Flows (IWMRRF), San Francisco, CA, June 19–21, 2013.
- K. Carlberg, R. Tuminaro, and P. Boggs, "Preserving Lagrangian Structure in Nonlinear Model Reduction," 2013 SIAM Conf on Comp Sci & Eng, Boston, MA, February 25–March 1, 2013.
- K. Carlberg, J. Ray, and B. van Bloemen Waanders, "A forecasting method for decreasing the temporal complexity in implicit, nonlinear model reduction," MoRePaS II, Gunzburg, Germany, October 2–5, 2012.
- K. Carlberg, C. Farhat, J. Cortial, and D. Amsallem, "The GNAT method for nonlinear model reduction: recent developments and application to large-scale models," 10th World Congress on Computational Mechanics, São Paulo, Brazil, July 8–13, 2012.
- K. Carlberg, J. Ray, and B. van Bloemen Waanders, "Decreasing the temporal complexity in nonlinear model reduction," 2012 SIAM Conf on Uncertainty Quantification, Raleigh, NC, April 2–5, 2012.
- K. Carlberg, D. Amsallem, C. Bou-Mosleh, and C. Farhat, "Efficient Model Reduction of Large-Scale Nonlinear Systems in Fluid Dynamics," 2011 SIAM Conf on Comp Sci & Eng, Reno, NV, February 28–March 4, 2011.
- K. Carlberg and C. Farhat, "Nonlinear model reduction using Petrov-Galerkin projection and data reconstruction," 2010 SIAM Annual Meeting, Pittsburgh, PA, July 13, 2010.
- K. Carlberg and C. Farhat, "A proper orthogonal decomposition-based augmented conjugate gradient algorithm for nearby problems," 2009 SIAM Annual Meeting, Denver, CO, July 7, 2009.
- K. Carlberg and C. Farhat, "An adaptive POD-Krylov reduced-order modeling framework for repeated analyses problems," 2009 Joint ASCE-ASME-SES Conf on Mechanics and Materials, Blacksburg, VA, June 27, 2009.
- K. Carlberg and C. Farhat, "A POD-based iterative solver for fast structural optimization," Seoul National University-Stanford University Student Joint Workshop, Stanford University, June 18, 2009.

Other skills

- C++, Matlab programming
- High-performance computing
- Unix
- LaTeX

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Other interests

- Marathons
- Backpacking
- Downhill skiing
- Triathlons
- Kayaking
- Home coffee roasting

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