

# Justin Werfel

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- Research Interests** Complex and emergent systems, swarm and modular robotics, social insect behavior, engineered molecular systems, evolutionary theory, morphogenesis, collective intelligence, amorphous/spatial computing, educational technology, bioinspired engineering.
- Education**
- Massachusetts Institute of Technology** Cambridge, MA  
Ph.D., Computer Science, June 9, 2006  
Minor: Brain & Cognitive Sciences  
Dissertation: Anthills Built to Order: Automating Construction with Artificial Swarms  
Advisors: Radhika Nagpal, H. Sebastian Seung
- Massachusetts Institute of Technology** Cambridge, MA  
S.M., Electrical Engineering and Computer Science, September 19, 2001  
GPA 5.0/5.0  
Thesis: Neural Network Models for Zebra Finch Song Production & Reinforcement Learning  
Advisor: H. Sebastian Seung
- Princeton University** Princeton, NJ  
A.B., Physics, June 1, 1999  
Minors: Biophysics, Engineering Physics, Applications of Computing, Applied & Computational Mathematics  
GPA 3.97/4.0; departmental GPA 3.97/4.0  
Phi Beta Kappa; cum laude  
Thesis: Topology and Dimensionality in Neural Network Memories  
Advisor: John Hopfield
- Appointments**
- Wyss Institute for Biologically Inspired Engineering, Harvard University Boston, MA  
Senior Research Scientist Nov 2014–present  
Staff Scientist—Bioinspired Robotics (Advanced Technology Team) Jun 2009–Oct 2014
- New England Complex Systems Institute Cambridge, MA  
Postdoctoral Fellow Sept 2007–May 2009
- Harvard Medical School/Children’s Hospital Boston Boston, MA  
Research Fellow Sept 2007–May 2009
- Harvard University, Electrical Engineering & Computer Science Cambridge, MA  
Postdoctoral Fellow Jul 2006–Aug 2007
- MIT, Computer Science & Artificial Intelligence Laboratory Cambridge, MA  
Research Affiliate Jun 2006–Jun 2012

## Publications

- Journals  
(refereed)
- Green, Ben, Paul Bardunias, J. Scott Turner, Radhika Nagpal, and Justin Werfel. Excavation and aggregation as organizing factors in de novo construction by mound-building termites. *Proceedings of the Royal Society B* **284**(1856): 20162730 (2017).
- Werfel, Justin, Donald E. Ingber, and Yaneer Bar-Yam. Theory and associated phenomenology for intrinsic mortality arising from natural selection. *PLoS ONE* **12**(3): e0173677 (2017).
- Werfel, Justin, Donald E. Ingber, and Yaneer Bar-Yam. Programmed death is favored by natural selection in spatial systems. *Physical Review Letters* **114**: 238103 (2015).
- Grun, Casey, Justin Werfel, David Yu Zhang, and Peng Yin. DyNAMiC Workbench: an integrated development environment for dynamic DNA nanotechnology. *Journal of the Royal Society Interface* (2015).
- Petersen, Kirstin, Paul Bardunias, Nils Napp, Justin Werfel, Radhika Nagpal, and J. Scott Turner. Arrestant property of recently manipulated soil on *Macrotermes michaelseni* as determined through visual tracking and automatic labeling of individual termite behaviors. *Behavioural Processes* **116**: 8-11 (2015).
- Werfel, Justin, Kirstin Petersen, and Radhika Nagpal. Designing collective behavior in a termite-inspired robot construction team. *Science* **343**: 754–758 (2014).
- Rutherford, Alex, Dion Harmon, Justin Werfel, Alexander S. Gard-Murray, Shlomiya Bar-Yam, Andreas Gros, Ramon Xulvi-Brunet, and Yaneer Bar-Yam. Good fences: the importance of setting boundaries for peaceful coexistence. *PLoS ONE* **9**(5): e95660 (2014).
- Werfel, Justin, Silva Krause, Ashley G. Bischof, Robert J. Mannix, Heather Tobin, Yaneer Bar-Yam, Robert M. Bellin, and Donald E. Ingber. How changes in extracellular matrix mechanics and gene expression variability might combine to drive cancer progression. *PLoS ONE* **8**(10): e76122 (2013).
- Wade, M.J., D.S. Wilson, C. Goodnight, D. Taylor, Y. Bar-Yam, M.A.M. de Aguiar, B. Stacey, J. Werfel, G.A. Hoelzer, E.D. Brodie III, P. Fields, F. Breden, T.A. Linksvayer, J.A. Fletcher, P.J. Richerson, J.D. Bever, J.D. Van Dyken, and P. Zee. Multilevel and kin selection in a connected world. *Nature* **463**: E8-E9 (2010).
- Werfel, Justin, and Radhika Nagpal. Three-dimensional construction with mobile robots and modular blocks. *International Journal of Robotics Research* **27**(3–4): 463–479 (2008).
- Werfel, Justin, and Radhika Nagpal. Extended stigmergy in collective construction. *IEEE Intelligent Systems* **21**(2): 20–28 (2006).
- Werfel, Justin, Xiaohui Xie, and H. Sebastian Seung. Learning curves for stochastic gradient descent in linear feedforward networks. *Neural Computation* **17**(12): 2699–2718 (2005).
- Werfel, Justin, and Yaneer Bar-Yam. The evolution of reproductive restraint through social communication. *Proceedings of the National Academy of Sciences* **101**(30):11019–11024 (2004).
- Mensch, Brett, Justin Werfel, and H. Sebastian Seung. BCI Competition 2003—data set Ia: combining gamma-band power with slow cortical potentials to improve single-trial classification of electroencephalographic signals. *IEEE Transactions on Biomedical Engineering* **51**(6):1052–1056 (2004).
- Niebur, Ernst, et al. Research, robots, and reality: a statement on current trends in biorobotics. *Behavioral and Brain Sciences* **24**(6):1072–1073 (2001).
- Werfel, Justin, Melanie Mitchell, and James P. Crutchfield. Effects of coevolution and resource sharing on the evolution of cellular automata. *IEEE Transactions on*

*Evolutionary Computation* 4(4): 388–393 (2000).

- Conferences (refereed)
- Melenbrink, Nathan, Panagiotis Michalatos, Paul Kassabian, and Justin Werfel. Using local force measurements to guide construction by distributed climbing robots. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2017)*, Vancouver, Canada (2017).
- Carey, Nicole, Radhika Nagpal, and Justin Werfel. Fast, accurate, small-scale 3D scene capture using a low-cost depth sensor. In *Proceedings of the IEEE Winter Conference on Applications of Computer Vision (WACV 2017)*, Santa Rosa, California (2017).
- Rubenstein, Michael, Bo Cimino, Radhika Nagpal, and Justin Werfel. AERobot: an affordable one-robot-per-student system for early robotics education. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 2015)*, Seattle, Washington (2015).
- Becker, Aaron, Golnaz Habibi, Justin Werfel, Michael Rubenstein, and James McLurkin. Massive uniform manipulation: controlling large populations of simple robots with a common input signal. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2013)*, Tokyo, Japan (2013).
- Rubenstein, Michael, Adrian Cabrera, Justin Werfel, Golnaz Habibi, James McLurkin, and Radhika Nagpal. Collective transport of complex objects by simple robots: theory and experiments. In *Proceedings of the 12th International Conference on Autonomous Agents and Multiagent Systems (AAMAS2013)*, Saint Paul, Minnesota, USA (2013).
- Petersen, Kirstin, Radhika Nagpal, and Justin Werfel. TERMES: an autonomous robotic system for three-dimensional collective construction. In *Proceedings of Robotics: Science and Systems VII (RSS 2011)*, Los Angeles, California (2011).
- Werfel, Justin. Biologically inspired primitives for engineered morphogenesis. In *Proceedings of the 7th International Conference on Swarm Intelligence (ANTS 2010)*, Brussels, Belgium (2010).
- Bailis, Peter, Radhika Nagpal, and Justin Werfel. Positional communication and private information in honeybee foraging models. In *Proceedings of the 7th International Conference on Swarm Intelligence (ANTS 2010)*, Brussels, Belgium (2010). **Winner of Best Student Paper Award; nominated for Best Paper Award.**
- Yu, Chih-Han, Justin Werfel, and Radhika Nagpal. Collective decision-making in multi-agent systems by implicit leadership. In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems (AAMAS-2010)*, Toronto, Canada (2010).
- Yu, Chih-Han, Justin Werfel, and Radhika Nagpal. Coordinating collective locomotion in an amorphous modular robot. In *Proceedings of the 2010 IEEE International Conference on Robotics and Automation (ICRA2010)*, Anchorage, Alaska (2010).
- Werfel, Justin, Donald Ingber, and Radhika Nagpal. Collective construction of environmentally-adaptive structures. In *Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2007)*, San Diego, California (2007).
- Werfel, Justin. Robot search in 3D swarm construction. In *Proceedings of the First IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO 2007)*, Cambridge, Massachusetts (2007).
- Werfel, Justin, Yaneer Bar-Yam, Daniela Rus, and Radhika Nagpal. Distributed construction by mobile robots with enhanced building blocks. In *Proceedings of the 2006 IEEE*

- International Conference on Robotics and Automation (ICRA 2006)*, Orlando, Florida (2006).
- Werfel, Justin, Yaneer Bar-Yam, and Radhika Nagpal. Building patterned structures with robot swarms. In *Proceedings of the Nineteenth International Joint Conference on Artificial Intelligence (IJCAI 2005)*, Scotland, UK, 1495–1502 (2005).
- Werfel, Justin. Building blocks for multi-agent construction. In *Distributed Autonomous Robotic Systems 6 (DARS 2004)*, Toulouse, France (2007).
- Werfel, Justin, Xiaohui Xie, and H. Sebastian Seung. Learning curves for stochastic gradient descent in linear feedforward networks. In *Advances in Neural Information Processing Systems 16 (NIPS 2003)*, Vancouver, Canada, 1197–1204 (2004).
- Workshops (refereed) Werfel, Justin. Embodied teachable agents: learning by teaching robots. *New Research Frontiers for Intelligent Autonomous Systems*, at 13<sup>th</sup> International Conference on Intelligent Autonomous Systems (IAS-13), Venice, Italy (2014).
- Petersen, Kirstin, Nils Napp, Jao-ke Chin-Lee, Justin Werfel, and Radhika Nagpal. 3D tracking of building processes in Macrotermes. *Workshop on Visual Observation and Analysis of Animal and Insect Behavior*, at 21st International Conference on Pattern Recognition (ICPR 2012), Tsukuba, Japan (2012).
- Werfel, Justin, Kirstin Petersen, and Radhika Nagpal. Distributed multi-robot algorithms for the TERMES 3D collective construction system. *Workshop on Reconfigurable Modular Robotics*, at IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS11), San Francisco, CA (2011).
- Werfel, Justin, Yaneer Bar-Yam, and Donald Ingber. Bioinspired environmental coordination in spatial computing systems. *Workshop on Spatial Computing*, at Second IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO 2008), Venice, Italy (2008).
- Werfel, Justin, and Radhika Nagpal. Towards a common comparison framework for global-to-local programming of self-assembling robotic systems. *Workshop on Self-Reconfigurable Robots & Systems and Applications*, at IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2007), San Diego, CA (2007).
- Werfel, Justin, and Radhika Nagpal. Three-dimensional directed construction. *Workshop on Self-Reconfigurable Modular Robots*, at *Robotics: Science and Systems II*, Philadelphia, PA (2006).
- Schuil, Crystal, Matthew Valente, Justin Werfel, and Radhika Nagpal. Collective construction using LEGO robots. In *Proceedings of the Twenty-First National Conference on Artificial Intelligence (AAAI 2006)*, Boston, MA (2006). Received Technical Innovation Award for “elegant connection of theory and design.”
- Technical Reports Werfel, Justin. Anthills built to order: Automating construction with artificial swarms. Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA; CSAIL Technical Report MIT-CSAIL-TR-2006-052 (2006).
- Rutherford, Alex, Dion Harmon, Justin Werfel, Shlomiya Bar-Yam, Alexander Gard-Murray, Andreas Gros, and Yaneer Bar-Yam. Good fences: the importance of setting boundaries for peaceful coexistence. arXiv:1110.1409 (2011).
- Werfel, Justin, and Yaneer Bar-Yam. Modeling, communication, and global catastrophe. *Knowledge Magazine* 1(1):5–13 (2009).
- Werfel, Justin, and Radhika Nagpal. Towards a common comparison framework for global-to-local programming of self-assembling robotic systems. *Harvard Computer Science Technical Report TR-14-07* (2007).

Werfel, Justin, Yaneer Bar-Yam, and Radhika Nagpal. Construction by robot swarms using extended stigmergy. AI Memo AIM-2005-011, MIT Computer Science and Artificial Intelligence Lab (2005).

Werfel, Justin. Implementing universal computation in an evolutionary system. AI Memo AIM-2002-010, MIT Artificial Intelligence Lab (2002).

Werfel, Justin. Neural network models for zebra finch song production and reinforcement learning. Master's thesis, Massachusetts Institute of Technology, Cambridge, MA; AI Technical Report AITR-2004-008 (2001).

Invited Book Chapters

Werfel, Justin, and Paul Kassabian. Towards automating construction with decentralized climbing robots and environmentally-adaptive, functionally-specified structures. In *Active Matter*, Skylar Tibbits and Leila Kinney, eds., MIT Press, 2017.

Werfel, Justin. Collective construction with robot swarms. In *Morphogenetic Engineering*, Rene Doursat, Hiroki Sayama, and Olivier Michel, eds., Springer, 2012.

Werfel, Justin. The ecology of Fraggie Rock. In *The Wider Worlds of Jim Henson*, Jennifer Garlen and Anissa Graham, eds., McFarland, 2013.

Grants

DARPA Seedling, “Engineering self-organizing systems: theory and topdown synthesis methodology for resilient collectives using Kilobot and molecular robotics platforms”, Radhika Nagpal (PI), Justin Werfel (co-PI), Peng Yin (co-PI), \$325,001, January 2017–January 2018.

NIH R01, “Modeling individual-to-collective behavior in mound-building termites”, Justin Werfel (PI), Radhika Nagpal (co-PI), J. Scott Turner (co-PI), \$1,859,193, September 2014–August 2019.

Wyss Institute Director’s Challenge Cross-Platform Grant, “Metamorpho: a robotic platform for emulating the developmental induction of locomotor patterns”, Eugene Goldfield, Radhika Nagpal, James Niemi, Justin Werfel, \$75,000, July 2014–June 2015.

Invited Talks

Union College, Computer Science Seminar and Biology Seminar, March 2, 2017

Australian National University, Biology Seminar, December 14, 2016

University of Technology Sydney, Faculty of Engineering and Information Technology Seminar, December 8, 2016

International Congress of Entomology, Symposium on Excavation and Construction by Social Insects, September 29, 2016

American Physical Society March Meeting, March 18, 2016

Technical University of Denmark, February 5, 2016

IT University of Copenhagen, February 4, 2016

Complex Systems Digital Campus World e-Conference, Engineering and Control of Self-Organization, September 30–October 1, 2015

**Keynote talk**, 13<sup>th</sup> European Conference on Artificial Life (ECAL 2015), July 20–24, 2015

University of Sheffield Automatic Control & Systems Engineering Seminar, July 17, 2015

O’Reilly Solid, June 23–25, 2015

Wellesley College Physics and Engineering Seminar, May 4, 2015

**Keynote talk**, 8<sup>th</sup> International Conference on Bio-inspired Information and Communications Technologies (BICT/BIONETICS), December 1–3, 2014

Georgia Tech Institute for Robotics and Intelligent Machines Seminar, October 29, 2014

**Keynote talk**, Workshop on Modular and Swarm Systems—From Nature to Robotics, at IEEE/RSJ International Conference on Intelligent Robots and Systems, Sept. 14, 2014

University of Colorado Boulder Computer Science Symposium, June 27, 2013  
Future Global Leaders Program, 2012–2014  
Queensland University of Technology, December 6, 2011  
Queensland Brain Institute, University of Queensland, December 5, 2011  
Future of Robotics Summit, Mass Technology Leadership Council, December 2, 2011  
Toyota Technological Institute at Chicago Colloquium, October 24, 2011  
Northwestern University Mechanical Engineering Seminar, October 24, 2011  
University of Pennsylvania GRASP Seminar, September 9, 2011  
Harvard Museum of Natural History, March 5, 2011  
Northeastern University, January 27, 2011  
iRobot Corporation, October 4, 2010  
Vrije Universiteit Amsterdam Artificial Intelligence Seminar, September 13, 2010  
**Keynote talk**, 3<sup>rd</sup> International Workshop on Guided Self-Organization, Indiana University, September 4–6, 2010  
University of Maryland Computer Science Colloquium, April 9, 2009  
Columbia University Electrical Engineering Seminar, March 26, 2009  
Indiana University School of Informatics Colloquium, March 5, 2009  
Rice University Computer Science Colloquium, February 12, 2009  
Vanderbilt University Electrical Engineering & Computer Science, February 5, 2009  
Grey Thumb Boston, February 2, 2009  
Brown University Computer Science Department Seminar, November 3, 2008  
University of Massachusetts Amherst Computer Science Department Seminar, Jan. 29, 2008  
Dartmouth University, Neukom Institute, June 11, 2007  
Charles River Associates, May 25, 2007  
Brandeis University Computer Science Colloquium, March 29, 2007  
Princeton University Computer Science Graphics/Media series, October 9, 2006  
International Conference on Complex Systems, June 27, 2006  
Sandia National Laboratories, March 14, 2006  
Icosystem Corporation, December 9, 2005  
University of Vermont Computer Science Seminar, December 5, 2005  
University of Vermont Biological Complexity Seminar, December 5, 2005  
MIT CSAIL Student Seminar, November 28, 2005  
MIT CSAIL Dangerous Ideas Seminar, March 31, 2005  
International Conference on Complex Systems, May 18, 2004  
MIT EECS Masterworks Forum, April 30, 2001  
Conference and workshop presentations for publications listed above

**Other  
Professional  
Activities**

Doctoral thesis examiner for Moises Pacheco (Technical University of Denmark), 2016; Anh Tuan Phan (Monash University), 2012.  
Honorary Associate of the University of Sydney, School of Civil Engineering, Faculty of Engineering and Information Technologies, 2015-2017.  
Chair (with Marco Mamei) of tracks on Self-Organization in Pervasive Distributed Systems (SOPDS 2008, 2009) at ACM Symposia on Applied Computing: ACM SAC 2008, Fortaleza, Brazil, March 16–20, 2008; and ACM SAC 2009, Honolulu, Hawaii, March 8–12, 2009.  
Organizer (with Jake Beal, Jonathan Bachrach, Olivier Michel, and Dan Yamins) of Spatial Computing Workshop at Second IEEE International Conference on Self-Adaptive and

- Self-Organizing Systems (SASO 2008), Venice, Italy, October 20, 2008.
- Chair (with Radhika Nagpal and Chih-Han Yu) of Multi-Robot Teaming Challenge at International Joint Conference on Artificial Intelligence (IJCAI-09), Pasadena, California, July 13-16, 2009.
- Editorial Board member for special issue of Swarm Intelligence journal on Swarm Robotics (2(2-4), December 2008).
- Program Committee member for Robotics: Science and Systems (RSS 2012), Distributed Autonomous Robotic Systems (DARS 2008, 2010, 2016), International Conference on Swarm Intelligence (ANTS 2010, 2014, 2016), International Symposium on Stabilization, Safety, and Security of Distributed Systems (SSS 2010), International Conference on Complex Systems (ICCS 2011), Genetic and Evolutionary Computation Conference (GECCO 2011, 2012, 2013, 2014), IEEE Symposium on Artificial Life (at IEEE SSCI 2011, 2013, 2015, 2017), Conference on the Synthesis and Simulation of Living Systems (ALIFE 2014, 2016), European Conference on Artificial Life (ECAL 2015, 2017), Bio-inspired Information and Communication Technologies (BICT 2017), Workshop on Self-Organizing Construction (at IEEE SASO 2016), Workshop on Guided Self-Organization (GSO-2016), Morphogenetic Engineering Workshop (MEW 2015), Swarm Robotics track at Bio-inspired Information and Communications Technologies (BICT 2015), AAI Robotics Fellowship (AAAI-15-RF), posters at IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO 2009).
- Reviewer for Science, IEEE Transactions on Robotics, International Journal of Robotics Research, Autonomous Robots, Swarm Intelligence, Artificial Life, PLOS Computational Biology, ACM Transactions on Autonomous and Adaptive Systems, IEEE Robotics and Automation Letters, IEEE International Conference on Robotics and Automation (ICRA 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015), IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011, 2012, 2013, 2014, 2015, 2016, 2017), IEEE Conference on Automation Science and Engineering (CASE 2010), International Conference on DNA Computing and Molecular Programming (DNA19).
- Invitee to Radcliffe Institute workshop “Programmable Molecular Robots and Nanobots: An Exploration of Possible Futures” (organized by Gal Kaminka and George Church), September 7–9, 2014, Cambridge, Massachusetts.
- Invitee to National Evolutionary Synthesis Center’s catalysis meeting “Evolution of Insect Sociality: An Integrative Modeling Approach”, October 14–17, 2010, Durham, NC.
- Participant in Telluride Neuromorphic Engineering Workshop, July 1–21, 2001, Telluride, Colorado.
- Participant in Methods in Computational Neuroscience course at Marine Biological Laboratory, August 2000, Woods Hole, Massachusetts.

**Teaching  
Experience**

- Lecturer for New England Complex Systems Institute biannual short courses on complexity, 2004–present.
- Supervisor for research (undergraduate, graduate, postdoctoral) at Harvard (2005–2007, 2009–present) and NECSI (2004–2009).
- Development TA for Introduction to Electrical Engineering and Computer Science (MIT 6.01), creating the first course in a new core sequence in MIT EECS undergraduate program, fall 2005, spring 2006: developed software and hardware infrastructure; wrote and tested problem sets, lab assignments, and other course materials; supervised and

evaluated coursework.

TA for Introduction to Computational Neuroscience (MIT 9.29), spring 2003, spring 2004: created and delivered lectures, edited and graded problem sets, led independent project groups.

Created curriculum for national STEM summer camp i2 Camp, “BugBots: Programming Mini-Robots”, introduction to programming and robotics for 5<sup>th</sup>–8<sup>th</sup> grades, 2014.

Designed and taught MIT Athletics Department juggling class, January 2005; Open Air Circus classes in unicycling, diabolo, and devil sticks, summer 2004; pantomime classes at MIT (2004) and Harvard (2011, 2012).

Computer science lab TA, Princeton, 1998–1999.

**Honors and Awards** Department of Defense National Defense Science & Engineering Graduate Fellowship, 1999.  
National Science Foundation Graduate Research Fellowship (declined), 1999.  
Fannie and John Hertz Foundation Finalist, 1999.  
Kusaka Memorial Prize in Physics, Princeton University, 1999.  
Phi Beta Kappa, 1999.  
MIT Arts Scholar, 2004-2006.

**Professional and Honor Societies** Sigma Xi, 1999-present.  
IEEE / Robotics & Automation Society, 2005-present.  
AAAI, 2006-2007.  
American Physical Society, 2015-2016.

**Hobbies and Interests** Glassblowing (MIT Glass Lab, Haystack); juggling (Princeton, MIT, Harvard Juggling Clubs); storytelling (The Moth [StorySLAM Winner], Story Collider, Massmouth [2<sup>nd</sup> place and Audience Choice awards at annual final competitions]); theater (Princeton Triangle Club, Theatre@First); a cappella (MIT Techiya); pantomime (MIT MIMeType, Princeton Movement Theatre, First Night Boston); fiction writing (*Active* member of the SFWA); puzzles (MIT Mystery Hunt, *Distractions* magazine); MIT GSC (Edgerton House, Graduate Ring Committee); cycling (bi- and uni-); archery; fencing (sabre); skiing; diving; hiking; music (Princeton University Band; piano, ukulele, and saw).