Summary of Naoki Saito's Research Accomplishments (as of September 2024)

Below, I describe only two most important lines of my research projects.
A bit more details of those as well as the other projects can be found at the following website:
https://www.math.ucdavis.edu/~saito/contrib/

I. Data adaptive multiscale basis dictionaries and applications

Ia: Description of contribution

Naoki Saito is a world expert on applied and computational harmonic analysis, in particular, its application to conventional and graph signal processing and analysis including feature extraction, pattern recognition, efficient approximation, and denoising, using the *adaptive multiscale basis dictionaries*, which are the vast extension of the conventional wavelet transforms. Saito developed fast algorithms of O(N log N) complexity to "rotate" the coordinates of input signal ensemble quickly so that the input data can be viewed from the new and better view angles, which allow one to select a small number of the most useful coordinates for a task at hand and to feed such coordinates to the standard module for the task, e.g., compression, denoising, classification, regression, etc. Saito also clarified the confusion between sparsity and statistical independence of the coordinates within the context of such basis dictionaries.
Saito is one of the early pioneers who developed interpretable machine learning techniques using these basis dictionaries and the basis selection algorithms: one can explicitly view the basis vectors corresponding to the selected coordinates used by these modules, which reveal their physically interpretable time-frequency information, which often leads to fundamental understanding of the underlying phenomena.
In addition, Saito's effort to lift the basis dictionaries originally developed for regularly sampled signals to much more general graph signals is quite remarkable. He and his group developed the *Hierarchical Graph Laplacian Eigen Transform (HGLET)*, the *Generalized Haar-Walsh Transform (GHWT), and the Natural Graph Wavelet Packets (NGWPs),* which generate graph versions of adaptive multiscale basis dictionaries. It is quite satisfying to see that if the input graph is a regular lattice graph, then the HGLET exactly generates the Hierarchical Block Discrete Cosine Transform Dictionary; the GHWT exactly generates the Haar-Walsh Wavelet Packet Dictionary; and the NGWPs exactly generates the Shannon Wavelet Packet Dictionary. Recently, Saito and his group even lifted the HGLET and GHWT to simplicial complexes (e.g., triangle meshes) so that those multiscale basis dictionaries are supported on edges, triangles, or tetrahedrons, etc. of an input graph.

Ib: Verifiable evidence

Saito and his collaborators published 37 papers on the multiscale basis dictionaries, which have been cited about 1900 times in total according to Google Scholar. In addition, [3, 6, 7] received as the *Best Paper Awards from the Society of Photo-Optical Instrumentation Engineers (SPIE) in 1994 and the Japan Society for Industrial and Applied Mathematics (JSIAM) in 2016, respectively.*

In fact, due to his contribution in this field, he was asked to be an associate editor for the highly respected three journals as listed in IV. The following list shows only the papers among those 30 that have been cited more than 100 times according to Google Scholar or those received best paper awards.

[1] N. Saito & G. Beylkin, "Multiresolution representations using the auto-correlation functions of compactly supported wavelets," *IEEE Trans. Signal Processing*, vol. 41, no. 12, pp. 3584-3590, 1993; Erratum: vol. 45, no. 3, p.768, 1997. Citations: 303

[2] N. Saito, "Simultaneous noise suppression and signal compression using a library of orthonormal bases and the minimum description length criterion," in *Wavelets in Geophysics* (E. Foufoula-Georgiou and P. Kumar, eds.), chap.XI, pp. 299-324, Academic Press, 1994. Citations: 317

[3] N. Saito & R. R. Coifman, "Local discriminant bases," in *Wavelet Applications in Signal and Image Processing II*, Proc. SPIE 2303, pp. 2-14, 1994. Best Paper Award. Citations: 253

[4] N. Saito & R. R. Coifman, "Local discriminant bases and their applications," *J. Mathematical Imaging and Vision*, vol. 5, no. 4, pp. 337-358, 1995. Invited Paper. Citations: 322

[5] N. Saito, R. R. Coifman, F. B. Geshwind, & F. Warner, "Discriminant feature extraction using empirical probability density estimation and a local basis library," *Pattern Recognition*, vol. 35, pp. 2841-2852, 2002. Citations: 109

[6] J. Irion & N. Saito, "Hierarchical graph Laplacian eigen transform," *JSIAM Letters*, vol. 6, pp. 21-24, 2014. Best Paper Award. Citations: 36

[7] N. Saito, "Applied harmonic analysis on graphs and networks," *Bulletin of the Japan Society for Industrial and Applied Mathematics*, vol. 25, no. 3, pp. 102-111, 2015 (in Japanese). Best Author Award. Citations: 4

Ic. Impact

Saito's methods have been examined and used in a variety of practical feature extraction and pattern classification problems including: digital hearing aids; diagnostics of digital mammograms; EMG pattern classification for limb prosthetics; classification of neural firing patterns; classification of heart rhythms in ECG signals; classification of soil types from soil surface roughness measurements; bank bill recognition for vending machines; radar target classification; classification of geological media using acoustic waveforms; discrimination of graphite-epoxy laminates; textile quality control in manufacturing processes; diagnostics of faults and performance degradation in electric power systems and equipment; diagnostics of condition and misfire of automobile engines; diagnostics of faults in oil refinery process, etc. For example, the WiHear system of Wang et al., which enables Wi-Fi signals to hear talks and conversations, successfully incorporates Saito's *local discriminant basis* (LDB) method for

extracting features from mouth motion. Moreover, the deep learning experts at Facebook appreciated Saito's foresight in interpretable machine learning and feature extraction.
In addition, the synthetic dataset called the *"Cylinder-Bell-Funnel" signals* that Saito created for signal classification experiments, emphasizing the interpretability of the underlying data generating mechanism, has become standard and been widely used when comparing the performance of various feature extractors and classifiers.

Id. Verifiable evidence of impact

The featured article "Wavelet Analysis," *IEEE Spectrum* 1996 October issue by A. Bruce, D. Donoho, & H.-Y. Gao reports:

"... For example, Naoki Saito, research scientist at Schlumberger-Doll Research, Ridgefield, Conn., and Ronald Coifman used S-Plus to develop novel schemes for signal classification employing wavelets [Fig. 7]. This application of wavelets has enormous potential--like neural networks, the schemes can be applied to an extensive range of problems in pattern recognition."

As for the WiHear system and another example described in Ic are:

- G. Wang, et al., "We can hear you with Wi-Fi!" *IEEE Trans. Mobile Comput.*, vol. 15, pp. 2907-2920, 2016.
- K. Englehart, B. Hudgins, & P. A. Parker, "A wavelet-based continuous classification scheme for multifunction myoelectric control," *IEEE Trans. Biomed. Eng.*, vol. 48, pp. 302-311, 2001.

As for the Facebook deep learning researchers' appreciation on Saito's methods, see:

- M. Tygert, J. Bruna, S. Chintala, Y. LeCun, S. Piantino, & A. Szlum, "A mathematical motivation for complex-valued convolutional networks," *Neural Comput.*, vol. 28, pp. 815-825, 2016.

As for the "Cylinder-Bell-Funnel" (CBF) signals, see:

- https://timeseriesclassification.com/description.php?Dataset=CBF
- https://www.cs.ucr.edu/%7Eeamonn/time_series_data_2018/

According to Dr. Eamonn Keogh who manages the time series archive at UC Riverside, the CBF dataset has been cited at least 1500 times according to the archive citation records.

II. Applications of Elliptic Boundary Value Problems for Signal and Image Processing

IIa. Description of contribution

Naoki Saito is a pioneer on utilizing boundary value problems (BVPs) for elliptic partial differential equations for practical signal and image processing and analysis applications. His investigation into the boundary/edge effect in local image analysis culminated in the invention

of *Polyharmonic Local Sine/Cosine Transforms* (PHLS/CT) and the use of *Laplacian eigenfunctions* for object-oriented image analysis and graph signal processing.
Both PHLST and PHLCT start with partitioning a given image into a set of rectangular blocks. Then, PHLST splits each block into a sum of the Dirichlet-Laplace BVP solution and the discrete sine polynomial while PHLCT does it into a sum of the Neumann-Poisson BVP solution and the discrete cosine polynomial. In particular, PHLCT exploits the infrastructure of the popular JPEG image compression standard, and accepts an existing JPEG file and decompresses it with higher quality with less blocking artifacts.
To analyze images supported on non-rectangular regions, Saito discovered that *the integral operator commuting with the Laplace operator* allows one to compute the Laplacian eigenfunctions in a numerically more stable yet fast manner without edge effects. This further allows one to partition an image into a set of non-rectangular segments and to compress, filter, and spectrally analyze each segment independently.

IIb. Verifiable evidence

Saito and his collaborators published 23 papers on the Laplacian-based signal processing methods, which have been cited more than 310 times in total according to Google Scholar. In addition, the idea developed in [10] has been patented in both Japan and US (see also IId). Paper [15] provided a solution (using the idea of *optimal transport*) to the long-standing problem of naturally organizing Laplacian eigenvectors according to their oscillation patterns and behaviors, not in terms of the corresponding eigenvalue size. This is quite important considering many graph signal processors erroneously view such eigenvalues as frequencies, which is only true if the underlying graph is either a simple path or a simple cycle.
The following lists only the papers among those 23 that have been cited more than 10 times according to Google Scholar.

[8] N. Saito & J.-F. Remy, "A new local sine transform without overlaps: A combination of computational harmonic analysis and PDE," in *Wavelets X*, Proc. SPIE vol. 5207, pp. 495-506, 2003. Citations: 13

[9] N. Saito & J.-F. Remy, "The polyharmonic local sine transform: A new tool for local image analysis and synthesis without edge effect," *Applied and Computational Harmonic Analysis*, vol. 20, no. 1, pp. 41-73, 2006. Citations: 41

[10] K. Yamatani & N. Saito, "Improvement of DCT-based compression algorithms using Poisson's equation," *IEEE Trans. Image Processing*, vol. 15, no. 12, pp. 3672-3689, 2006. Citations: 41

[11] N. Saito, "Data analysis and representation on a general domain using eigenfunctions of Laplacian," *Applied and Computational Harmonic Analysis*, vol. 25, no. 1, pp. 68-97, 2008. Citations: 83

[12] N. Saito & E. Woei, "Analysis of neuronal dendrite patterns using eigenvalues of graph Laplacians," *JSIAM Letters*, vol. 1, pp. 13-16, 2009. Citations: 17

[13] N. Saito & E. Woei, "On the phase transition phenomenon of graph Laplacian eigenfunctions on trees," *RIMS Kôkyûroku*, vol. 1743, pp. 77-90, 2011. Citations: 20

[14] Y. Nakatsukasa, N. Saito, & E. Woei, "Mysteries around graph Laplacian eigenvalue 4," *Linear Algebra and its Applications*, vol. 438, no. 8, pp. 3231-3246, 2013. Citations: 37

[15] N. Saito, "How can we naturally order and organize graph Laplacian eigenvectors?" *Proc. 2018 IEEE Workshop on Statistical Signal Processing*, pp. 483-487, 2018. Citations: 26

IIc. Impact

Because PHLCT can improve the quality of existing JPEG-compressed files, Saito and his collaborator through their respective universities applied for patent applications in Japan and US, and successfully obtained two patents.
Moreover, a large Japanese corporation, *Yamaha Corp.*, licensed this algorithm and implemented it in their 2D graphics LSI chip for amusement game machines. Furthermore, Lionel Moisan (Univ. Paris Descartes) was inspired by PHLST/PHLCT, and proposed his "periodic plus smooth image decomposition."
As for the integral operator commuting with the Laplacian, it has drawn considerable attentions from pure mathematicians to application domain experts. The former includes M. Ruzhansky (Imperial College, London) and his collaborators who have extended Saito's operator to all sorts of related potential operators while the latter includes Faisal Beg (Simon Fraser Univ.) who used it for his 3D hippocampus shape analysis for detecting early Alzheimer's disease and Tim DelSole (George Mason Univ.) who used it to compute the Laplacian eigenfunctions of the continental part and the oceanic part of the world separately for his climate data analysis. In addition, Saito also co-organized many minisymposia on this subject at various conferences, and 5 day workshops at IPAM in Feb. 2009 and at BIRS in Mar. 2015.

IId. Verifiable evidence of impact

The two patents mentioned in IIc:

- K. Yamatani & N. Saito, "DATA COMPRESSION/DECOMPRESSION METHOD, PROGRAM, AND DEVICE," Japan Patent Number 4352110, Granted 8/7/2009.
- K. Yamatani & N. Saito, "Data compression-decompression method, program, and electronic device," US Patent Number 8059903, Granted 11/15/2011.

The LSI chip information mentioned in IIc:

- https://device.yamaha.com/ja/lsi/products/graphic_controller/images/PBGV635A-001-02-j.pdf
- https://device.yamaha.com/en/lsi/products/graphic_controller/ (See GP-2 section)

Papers mentioned in IIc that cite Saito's papers:

- L. Moisan, "Periodic plus smooth image decomposition," *J. Mathematical Imaging and Vision*, vol. 39, pp. 161-179, 2011.
- M. Ruzhansky & D. Suragan, "Layer potentials, Kac's problem, and refined Hardy inequality on homogeneous Carnot groups," *Adv. Math.*, vol. 308, pp. 483-528, 2017.
- M. Ruzhansky & D. Suragan, "On Kac's principle of not feeling the boundary for the Kohn Laplacian on the Heisenberg group," *Proc. Amer. Math. Soc.*, vol. 144, pp. 709-721, 2016.
- M. Ruzhansky & Suragan, "Isoperimetric inequalities for the logarithmic potential operator," *J. Math. Anal. Appl.*, vol. 434, pp. 1676-1689, 2016.
- M. F. Beg, et al., "Comparison of four shape features for detecting hippocampal shape changes in early Alzheimer's," *Stat. Methods Med. Res.*, vol. 22, pp. 439-462, 2013.
- T. DelSole & M. K. Tippett, "Laplacian eigenfunctions for climate analysis," *J. Climate*, vol. 28, pp. 7420-7436, 2015.

III. Honors and Awards

- Best Paper Award for the Wavelet Applications in Signal and Image Processing II, SPIE - The International Society for Optical Engineering, International Symposium, Jul. 1994.

- The Henri G. Doll Award (the highest honor in the technical papers within the Schlumberger organization), Jun. 1997.

- Elevation to IEEE Senior Member, Dec. 1999.

- Office of Naval Research Young Investigator Award, Feb. 2000.

- Presidential Early Career Award for Scientists and Engineers (PECASE), Oct. 2000.

- 2016 JSIAM Letters Best Paper Award (jointly with Jeff Irion) from the Japan Society for Industrial and Applied Mathematics (JSIAM) for the article "Hierarchical graph Laplacian eigen transforms," JSIAM Letters, vol.6, pp.21-24, 2014.

- 2016 Best Author Award from the Japan Society for Industrial and Applied Mathematics (JSIAM) for the article "Applied Harmonic Analysis on Graphs and Networks," (in Japanese), Bulletin of JSIAM, vol.25, no.3, pp.6-15, 2015.

- Invitation to the National Academies Keck Futures Initiative (NAKFI) conference "Beyond Boundaries: 15 Years of Exploring Intersections in Science, Engineering, and Medicine," Irvine, CA, 11/08/17-11/11/17.

- Invitation to the National Academies Keck Futures Initiative (NAKFI) conference "Collective Behavior: From Cells to Societies," Irvine, CA, 11/13/14-11/15/14.

- Invitation to the National Academies Keck Futures Initiative (NAKFI) conference: "Seeing the Future with Imaging Science," Irvine, CA, 11/17/10-11/19/10.

- Invitation to the symposium "Frontiers of Science," organized by the National Academy of Sciences, Nov. 2003.

- Invitation to the workshop on "Approaches to Combat Terrorism: Opportunities for Basic Research," co-organized by NSF and US Intelligence Community, Nov. 2002.

- Elevation to IEEE *Life* Senior Member, Jan. 2024.

IV. Synergetic Activities

- Associate Editor of the journal "Applied and Computational Harmonic Analysis" (Impact Factor: 2.573), 2007-present

- Associate Editor of the journal "Inverse Problems and Imaging" (Impact Factor: 1.373), 2008-present

- Editorial Board Member of the "Journal of Mathematical Imaging and Vision" (Impact Factor: 1.353), 2014-present

- Served as Chair of SIAM Activity Group on Imaging Science (SIAG/IS) (term: Jan. 2014-Dec. 2015); served as its Vice Chair (term: Jan. 2012-Dec. 2013); served as Chair of the SIAG/IS Prize Committee, 2013.

- Co-organized a semester-long program "Multiscale Geometry and Analysis in High Dimensions" at the Institute for Pure and Applied Mathematics (IPAM), UCLA, Fall 2004.

- Co-organized a week-long program "Laplacian eigenvalues and eigenfunctions: Theory, Computation, Application" at IPAM, UCLA, Feb. 2009.

- Co-organized a special session on "Kernel Methods in Data Analysis" at the IEEE Workshop on Statistical Signal Processing, Cardiff, UK, Sep. 2009.

- Delivered a 3-hour tutorial on "Harmonic Analysis on and of Irregular Domains, Graphs, and Networks" at the IEEE Workshop on Statistical Signal Processing, Gold Coast, Australia, Jun. 2014.

- Co-organized a 5-day workshop on "Laplacians and Heat Kernels: Theory and Applications" at the Banff International Research Station (BIRS), Canada, Mar. 2015.

- Co-organized seven minisymposia: International Congress of Industrial and Applied Mathematics (ICIAM), Tokyo, Aug. 2024; Valencia, Jul. 2019; Vancouver, Jul. 2011; Zurich, Jul. 2007; SIAM Conference on Imaging Science, San Diego, Jul. 2008; Joint Mathematics Meetings, San Francisco, Jan. 2010; SIAM Annual Meeting, San Diego, Jul. 2013; Joint Mathematics Meetings, Baltimore, Jan. 2014.

- Served as a member of Program Committee of SPIE Conference on Wavelets, 1998-2007; 2014-2017.

- Served as an NSF Review Panelist, 2005, 2008, 2013, 2016, 2019, 2023.