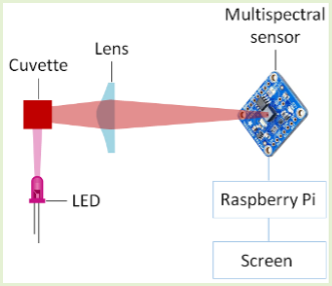
Multiplex Detection with Multispectral Sensors and Machine Learning

First A. Author, *Fellow, IEEE*, Second B. Author, and Third C. Author, Jr., *Member, IEEE*

***Abstract*— Multiplex assays usually use probes with different spectroscopic signatures to detect two or more analytes simultaneously. By allowing researchers to test for multiple markers per sample, they give a more reliable picture of what is happening. Being available in multiple colors and able to be conjugated to biomolecules, quantum dots are ideal as labels in multiplex assays. As a proof-of-concept, we demonstrate the capability of these multispectral sensors, using various machine learning appraoches, for multiplex detection by using mixtures of quantum dots of two different colors. We show that the sensors can detect quantum dot concentrations relevant to biological applications by combining our sensor readings with ML algorithm running a Raspberry Pi Zero. We implement a 5 distinct types of ML algorithms to predict the QD concentration, along with various tools for training, evaluation, and utilizing a model.**



***Index Terms*— Enter key words or phrases in alphabetical order, separated by commas. For a list of suggested keywords, send a blank e-mail to keywords@ieee.org or visit http://www.ieee.org/organizations/pubs/ani_prod/keywrd98.txt**

I. Introduction

COLORIMETRIC and luminescent assays are tests that generate colored reactants or fluorescence when an analyte of interest is present in a sample. They are widely used in biosensing, such as in disease diagnosis, food safety testing, environmental monitoring, and quality control. Since their signals are obtained through the spectral analysis of light, the detectors needed for these assays can be complex, bulky, and expensive. They often require trained personnel to maintain and operate them. These factors can slow, or even prevent, diagnosis in resource-limited regions. Imaging-based technologies such as smartphone spectrometers have been touted as solutions to make biosensing accessible worldwide. However, they need complicated procedures for calibrating the wavelength scale and converting digital images into spectra. (details about what is complicated about the procedures) Moreover, users have limited control over camera parameters. It restricts their application to areas where people have the technical know-how to set them up properly in order to get reproducible image quality. Inexpensive multispectral sensors have recently been introduced commercially, and they have none of these constraints of imaging-based technologies. They require no calibration by the user as they come fitted with Gaussian interference filters and can monitor the following wavelengths simultaneously, with a full-width at half-maximum of 40 nm: 450 nm, 500 nm, 550 nm, 570 nm, 600 nm, and 650 nm. This set of wavelengths is adequate for many colorimetric, fluorescent, and luminescent assays. Being easy to assemble, troubleshoot and operate, these multispectral sensors are appealing to resource-limited laboratories. They have, for example, been interfaced with a Raspberry Pi Zero to produce a simple colorimetric reader for bio-assays. They are also versatile and can be found in applications ranging from wireless capsule endoscopy prototypes to systems characterizing microfluidic chips. In this work, we demonstrate their potential for multiplex detection. kkk

A. Multiplex Applications of QDs

Multiplex assays usually use probes with different spectroscopic signatures to detect two or more analytes simultaneously. By allowing researchers to test for multiple markers per sample, they give a more reliable picture of what is happening. Consider, for example, a patient coming to a clinic with respiratory symptoms. The physician may take a sample from the patient, and if they have access to single-plex tests only, they will test for the pathogen they suspect is most likely responsible for the respiratory problem. If the test comes out

This paragraph of the first footnote will contain the date on which you submitted your paper for review. It will also contain support information, including sponsor and financial support acknowledgment. For example, “This work was supported in part by the U.S. Department of Commerce under Grant BS123456.”

The next few paragraphs should contain the authors’ current affiliations, including current address and e-mail. For example, F. A. Author is with the National Institute of Standards and Technology, Boulder, CO 80305 USA (e-mail: author@boulder.nist.gov).

S. B. Author, Jr., was with Rice University, Houston, TX 77005 USA. He is now with the Department of Physics, Colorado State University, Fort Collins, CO 80523 USA (e-mail: author@lamar.colostate.edu).

T. C. Author is with the Electrical Engineering Department, University of Colorado, Boulder, CO 80309 USA, on leave from the National Research Institute for Metals, Tsukuba, Japan (e-mail: author@nrim.go.jp).

negative, they will need another sample and will have to test for another pathogen. In essence, the physician is using an elimination process for diagnosis. A multiplex test that screens the patient for multiple pathogens simultaneously will expedite the diagnosis process. Being available in multiple colors and able to be conjugated to biomolecules, quantum dots are ideal as labels in multiplex assays. They have, for example, been used to quantify the amount of cholera toxin, ricin, shiga-like toxin 1, and staphylococcal enterotoxin B in a sample. Multiplex analysis based on quantum dots have also been developed to identify illicit substances such as dexamethasone, gentamicin, clonazepam, medroxyprogesterone acetate, and ceftiofur. More recently, they have been applied to detect multiple tumor markers, or to monitor the activity of protease enzymes such as trypsin, chymotrypsin and enterokinase. As a proof-of-concept, we demonstrate the capability of these multispectral sensors, using various machine learning appraoches, for multiplex detection by using mixtures of quantum dots of two different colors. We show that the sensors can detect quantum dot concentrations relevant to biological applications.

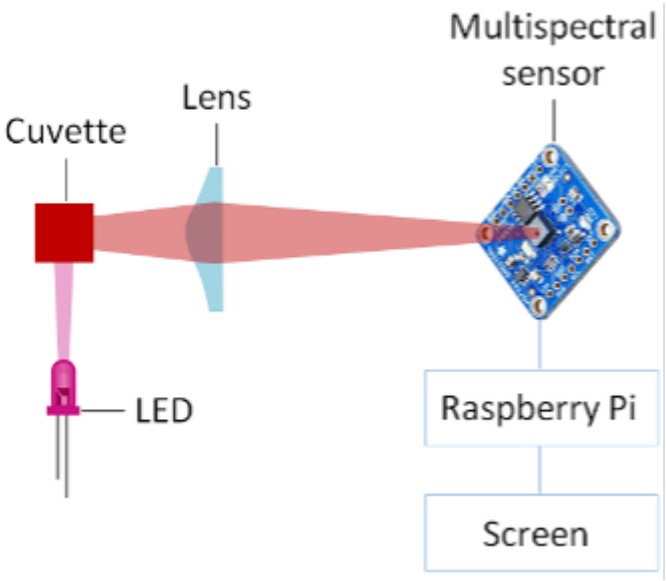


Fig. 1. Magnetization as a function of applied field. It is good practice to explain the significance of the figure in the caption.

B. Machine learning background

In order to make rapid predictions with some acquired training data, we use some popular machine learning algorithms. Machine learning has been used for detection, quantification, and classification of past/current events, prediction of future ones or even self-calibratio (cite 1,2,3,4). For instance, *give a few examples*. In sensing applications, the ML algorithms are typically implemented digitally on general-purpose microprocessors (cite ML for sensor data), or (smart phone application?). In this paper we implement combine our sensor readings with ML algorithm using a cheap and widely accessible SBC: Raspberry Pi Zero. We implement a 5 distinct types of ML algorithms to predict the QD concentration, along with various tools for training, evaluation, and utilizing a mode.

II. Methods

A. Sensor System

Our system uses a commercially available multispectral sensor (Adafruit AS7341). Its data are read and processed with a standard I2C bus on an appropriate microcontroller, which was a Raspberry Pi Zero in our case. The system can be tailored to different applications since the software to run it is written in the Python language and can easily be modified. The microcontroller gives users the ability to attach a screen to view the data, or to transfer the results to another location via WiFi.

B. Set up for testing our sensing system

The SI unit for magnetic field strength

C. Description of Machine learning algorithms

We use supervised machine learning to predict the QD concentration from the eight wavelength intensities. For each observation x_i for $i = 1, 2, .., n$ there is an associated response measurement y_i. The goal during training, is to approximate a mapping function from the input x to the output y variable, so that when given a new set of unknown input data, the algorithm can correctly predict the correct output variable. To avoid potential overfitting of the data, we have use a 10 fold-cross validation scheme. (some info about regression vs classifcastion?) We have tried 5 distinct types of common ML algorithms to predict the QD concentration. In this section we provide a shot description and key properties of each ML algorithm. (following the style of Subhendu Pandit paper)

One possible approach to predict multiple QD types is to train a model for each emitter of interest, this approach is flexible but more computationally and memory expensive. If using this scheme, during inference time we run all models in sequence. Alternatively, we could train our models to predict in a multivariate fashion, we discuss this possibility according to each algorithm.

Gaussian process regression: is nonparametric, meaning the data is not assumed to belong to any particular parametric family of probability distributions (cite x), so rather than calculating the probability distribution of parameters of a specific function, gaussian process regression calculates the probability distribution over all admissible functions that fit the data. However, we specify a function space prior, calculate the posterior using the training data, and compute the predictive posterior distribution on our points of interest.GP has been proven to be an effective method for nonlinear problems due to many desirable properties, such as a clear structure with Bayesian interpretation, a simple integrated approach of obtaining and expressing uncertainty in predictions and the capability of capturing a wide variety of data feature by hyper-

parameters [13, 2]. The classical GP model can be only used to deal with a single output or single response problem however there are various ways to apply gaussian process regression with multiple response variables (cite)

Regression MLP: Multi-level Perceptron (MLP) is a neural network connecting several layers of input nodes as a directed graph, tasks with predicting an output variable as a function of the inputs. The input features can be categorical or numeric types, however, for regression NN, we require a numeric dependent variable. The multiple layers and non-linear activation allow the MLP to learn non linear features. To make multivariate predictions we simply increase number of neurons in our output layer.

Random Forest: A random forest fits a number of classifying decision trees on various sub-samples of the dataset and uses averaging to improve the predictive accuracy and control over-fitting. Random forests also require less hyper-parameter tuning than other methods discussed here, with the exception of Linear regression. To make multivariate predictions we simply increase the output layer

SVM Regression: Support Vector Machine is a supervised learning algorithm that is used to predict discrete values. Support Vector Regression uses the same principle as the SVMs. A support-vector machine constructs a hyperplane or set of hyperplanes in a high- or infinite-dimensional space, which can be used for classification, regression, or other tasks like outliers detection (cite). Im actually not sure how to do multivariate for this example yet.

Linear regression: In a linear model, e.g. a model that assumes a linear relationship between the input variables (x) and the single output variable (y). More specifically, that y can be calculated from a linear combination of the input variables (x). When there is a single input variable, the method is referred to as simple linear regression otherwise we have multivariate example. Furthermore, to make multiple output predictions we extend linear regression however this can be shown to be same as independently solving a separate regression problem for each response variable.

1) Frequentist vs Bayesian Models: here we discuss the key differences in assumptions and applications between bayesian methods and frequentist methods. Also discuss confidence intervals, and some considerations when comparing models.

D. Training Details

Here we can discuss general training details. Epochs, libraries we used. and other compute details

1) Hyper-parameter Optimization: Every algorithm attempted here has various hyper-parameters that affect the corresponding optimization process. These can have a significant difference in learning, so its important we employ a search to find optimal hyper-parameters. I think we can make a table in appendix showing optimal hyperparameters

III. Results

A. Characterizing the limit of detection

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

TABLE I
MACHINE LEARNING MODELS

Model	Type	Accuracy*	Trainable Parameters
Gaussian Process Reggression	Univariate	4.5	N/A**
Linear Regression	Univariate	4.5	1
Bayesian Regression	Univariate	4.5	1
Random Forest Regession	Univariate	4.5	1
Neural Network	Univariate	4.5	1
Neural Network	Multiivariate	4.5	1

*Accuracy is measure of MSE for 10-fold Cross val. All models were tested using the same cross validation dataset breakdown. For univaraite models accuracy is the average between the two models
**Bayesian methods are non-parametric and therefore have no trainable parameters

B. Model Selection

1) Metrics: kk A Cost Function is used to evaluate the performance of a Model on data. Mean squared error (MSE) is a common measure for evaluating the performance of a model which sums (or averages) the square of the difference between estimated and true values over the population. The main motivation for using MSE is its differentiability which simplifies the Cost Function minimization process. An alternative metric is the Mean absolute error (MAE) (i.e., the sum/average of absolute values of the differences between estimations and observed outputs) which is sometimes employed for sequential/temporal data processing. As mentioned before, training is achieved through by adjusting the weights (i.e., elements of vector ?? in Eq. 1) kk.

Here we discuss cross validation accuracy and BIC, AIC criterial?

2) Confidence interval for Bayesian Methods: Figures that are composed of only black lines and shapes. These figures should have no shades or half-tones of gray, only black and white.

C. Making Predictions

1) Raspberry Pi Details: Figures that are composed of only black lines and shapes. These figures should have no shades or half-tones of gray, only black and white.

2) Confidence Intervals for retraining: Figures that are composed of only black lines and shapes. These figures should have no shades or half-tones of gray, only black and white.

IV. Conclusion

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions. A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

Appendixes, if needed, appear before the acknowledgment.

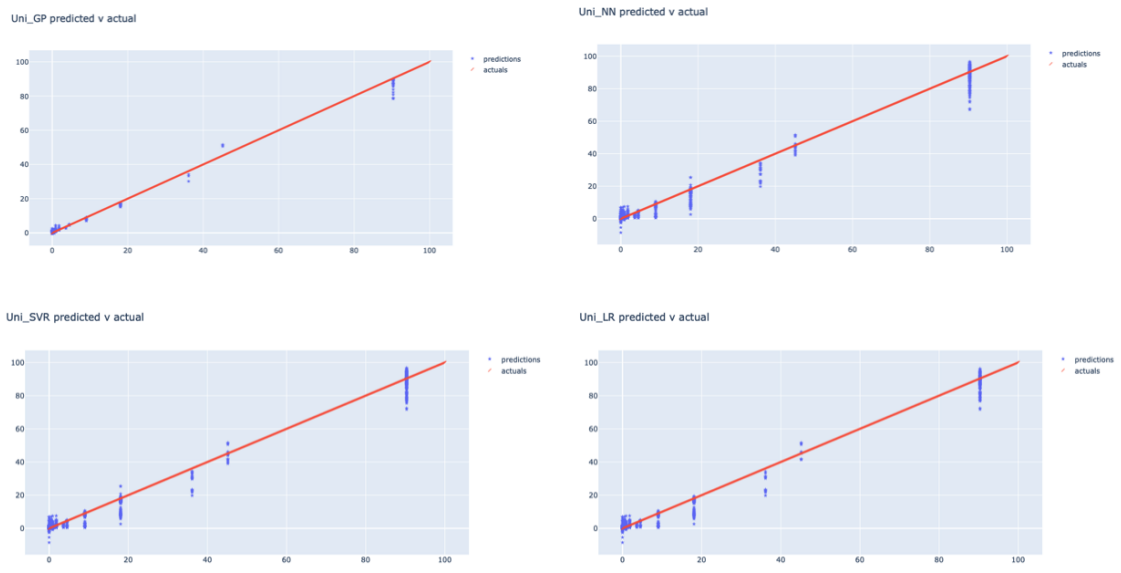


Fig. 2. Magnetization as a function of applied field. It is good practice to explain the significance of the figure in the caption.

ACKNOWLEDGMENT

The preferred spelling of the word "acknowledgment" in American English is without an "e" after the "g." Use the singular heading even if you have many acknowledgments. Avoid expressions such as "One of us (S.B.A.) would like to thank . . . ." Instead, write "F. A. Author thanks . . . ." In most cases, sponsor and financial support acknowledgments are placed in the unnumbered footnote on the first page, not here.

REFERENCES AND FOOTNOTES

A. References

References need not be cited in text. When they are, they appear on the line, in square brackets, inside the punctuation. Multiple references are each numbered with separate brackets. When citing a section in a book, please give the relevant page numbers. In text, refer simply to the reference number. Do not use "Ref." or "reference" except at the beginning of a sentence: "Reference [3] shows . . . ." Please do not use automatic endnotes in *Word*, rather, type the reference list at the end of the paper using the "References" style.

Reference numbers are set flush left and form a column of their own, hanging out beyond the body of the reference. The reference numbers are on the line, enclosed in square brackets. In all references, the given name of the author or editor is abbreviated to the initial only and precedes the last name. Use them all; use *et al.* only if names are not given. Use commas around Jr., Sr., and III in names. Abbreviate conference titles. When citing IEEE transactions, provide the issue number, page range, volume number, year, and/or month if available. When referencing a patent, provide the day and the month of issue, or application. References may not include all information; please obtain and include relevant information. Do not combine references. There must be only one reference with each number. If there is a URL included with the print reference, it can be included at the end of the reference.

Other than books, capitalize only the first word in a paper title, except for proper nouns and element symbols. For papers published in translation journals, please give the English citation first, followed by the original foreign-language citation See the end of this document for formats and examples of common references. For a complete discussion of references and their formats, see the IEEE style manual at http://www.ieee.org/authortools.

B. Footnotes

Number footnotes separately in superscript numbers.[1] Place the actual footnote at the bottom of the column in which it is cited; do not put footnotes in the reference list (endnotes). Use letters for table footnotes (see Table I).

APPENDIX I
SUBMITTING YOUR PAPER FOR REVIEW

A. Final Stage

When you submit your final version (after your paper has been accepted), print it in two-column format, including figures and tables. You must also send your final manuscript on a disk, via e-mail, or through a Web manuscript submission system as directed by the society contact. You may use *Zip* for large files, or compress files using *Compress, Pkzip, Stuffit,* or *Gzip.*

Also, send a sheet of paper or PDF with complete contact information for all authors. Include full mailing addresses, telephone numbers, fax numbers, and e-mail addresses. This information will be used to send each author a complimentary

[1]It is recommended that footnotes be avoided (except for the unnumbered footnote with the receipt date on the first page). Instead, try to integrate the footnote information into the text.

copy of the journal in which the paper appears. In addition, designate one author as the "corresponding author." This is the author to whom proofs of the paper will be sent. Proofs are sent to the corresponding author only.

B. Review Stage Using ScholarOne® Manuscripts

Contributions to the Transactions, Journals, and Letters may be submitted electronically on IEEE's online manuscript submission and peer-review system, ScholarOne® Manuscripts. You can get a listing of the publications that participate in ScholarOne at http://www.ieee.org/publications_standards/publications/authors/authors_submission.html. First check if you have an existing account. If there is none, please create a new account. After logging in, go to your Author Center and click "Submit First Draft of a New Manuscript."

Along with other information, you will be asked to select the subject from a pull-down list. Depending on the journal, there are various steps to the submission process; you must complete all steps for a complete submission. At the end of each step you must click "Save and Continue"; just uploading the paper is not sufficient. After the last step, you should see a confirmation that the submission is complete. You should also receive an e-mail confirmation. For inquiries regarding the submission of your paper on ScholarOne Manuscripts, please contact oprs-support@ieee.org or call +1 732 465 5861.

ScholarOne Manuscripts will accept files for review in various formats. Please check the guidelines of the specific journal for which you plan to submit.

You will be asked to file an electronic copyright form immediately upon completing the submission process (authors are responsible for obtaining any security clearances). Failure to submit the electronic copyright could result in publishing delays later. You will also have the opportunity to designate your article as "open access" if you agree to pay the IEEE open access fee.

C. Final Stage Using ScholarOne Manuscripts

Upon acceptance, you will receive an email with specific instructions regarding the submission of your final files. To avoid any delays in publication, please be sure to follow these instructions. Most journals require that final submissions be uploaded through ScholarOne Manuscripts, although some may still accept final submissions via email. Final submissions should include source files of your accepted manuscript, high quality graphic files, and a formatted pdf file. If you have any questions regarding the final submission process, please contact the administrative contact for the journal.

In addition to this, upload a file with complete contact information for all authors. Include full mailing addresses, telephone numbers, fax numbers, and e-mail addresses. Designate the author who submitted the manuscript on ScholarOne Manuscripts as the "corresponding author." This is the only author to whom proofs of the paper will be sent.

D. Copyright Form

Authors must submit an electronic IEEE Copyright Form (eCF) upon submitting their final manuscript files. You can access the eCF system through your manuscript submission system or through the Author Gateway. You are responsible for obtaining any necessary approvals and/or security clearances. For additional information on intellectual property rights, visit the IEEE Intellectual Property Rights department web page at http://www.ieee.org/publications_standards/publications/rights/index.html.

Appendix II
IEEE Publishing Policy

The general IEEE policy requires that authors should only submit original work that has neither appeared elsewhere for publication, nor is under review for another refereed publication. The submitting author must disclose all prior publication(s) and current submissions when submitting a manuscript. Do not publish "preliminary" data or results. The submitting author is responsible for obtaining agreement of all coauthors and any consent required from employers or sponsors before submitting an article. The IEEE Transactions and Journals Department strongly discourages courtesy authorship; it is the obligation of the authors to cite only relevant prior work.

The IEEE Transactions and Journals Department does not publish conference records or proceedings, but can publish articles related to conferences that have undergone rigorous peer review. Minimally, two reviews are required for every article submitted for peer review.

Appendix III
Publication Principles

The two types of contents of that are published are; 1) peer-reviewed and 2) archival. The Transactions and Journals Department publishes scholarly articles of archival value as well as tutorial expositions and critical reviews of classical subjects and topics of current interest.

Authors should consider the following points:

1) Technical papers submitted for publication must advance the state of knowledge and must cite relevant prior work.
2) The length of a submitted paper should be commensurate with the importance, or appropriate to the complexity, of the work. For example, an obvious extension of previously published work might not be appropriate for publication or might be adequately treated in just a few pages.
3) Authors must convince both peer reviewers and the editors of the scientific and technical merit of a paper; the standards of proof are higher when extraordinary or unexpected results are reported.
4) Because replication is required for scientific progress, papers submitted for publication must provide sufficient information to allow readers to perform similar experiments or calculations and use the reported results. Although not everything need be disclosed, a paper must contain new, useable, and fully described information. For example, a specimen's chemical composition need

not be reported if the main purpose of a paper is to introduce a new measurement technique. Authors should expect to be challenged by reviewers if the results are not supported by adequate data and critical details.

5) Papers that describe ongoing work or announce the latest technical achievement, which are suitable for presentation at a professional conference, may not be appropriate for publication.

APPENDIX IV
REFERENCE EXAMPLES

- *Basic format for books:*
  J. K. Author, "Title of chapter in the book," in *Title of His Published Book, x*th ed. City of Publisher, (only U.S. State), Country: Abbrev. of Publisher, year, ch. x, sec. x, pp. *xxx–xxx.*
  See [1], [2].
- *Basic format for periodicals:*
  J. K. Author, "Name of paper," *Abbrev. Title of Periodical*, vol. *x, no*. x,pp. *xxx–xxx,* Abbrev. Month, year, DOI. 10.1109.*XXX*.123456.
  See [3]– [5].
- *Basic format for reports:*
  J. K. Author, "Title of report," Abbrev. Name of Co., City of Co., Abbrev. State, Country, Rep. *xxx*, year.
  See [6], [7].
- *Basic format for handbooks:*
  Name of Manual/Handbook, x ed., Abbrev. Name of Co., City of Co., Abbrev. State, Country, year, pp. *xxx–xxx.*
  See [8], [9].
- *Basic format for books (when available online):*
  J. K. Author, "Title of chapter in the book," in *Title of Published Book*, xth ed. City of Publisher, State, Country: Abbrev. of Publisher, year, ch. x, sec. x, pp. *xxx–xxx*. [Online]. Available: http://www.web.com
  See [10]– [13].
- *Basic format for journals (when available online):*
  J. K. Author, "Name of paper," *Abbrev. Title of Periodical*, vol. x, no. x, pp. *xxx–xxx*, Abbrev. Month, year. Accessed on: Month, Day, year, DOI: 10.1109.*XXX*.123456, [Online].
  See [14]– [16].
- *Basic format for papers presented at conferences (when available online):*
  J.K. Author. (year, month). Title. presented at abbrev. conference title. [Type of Medium]. Available: site/path/file
  See [17].
- *Basic format for reports and handbooks (when available online):*
  J. K. Author. "Title of report," Company. City, State, Country. Rep. no., (optional: vol./issue), Date. [Online] Available: site/path/file
  See [18], [19].
- *Basic format for computer programs and electronic documents (when available online):*
  Legislative body. Number of Congress, Session. (year, month day). *Number of bill or resolution*, *Title*. [Type of medium]. Available: site/path/file
  ***NOTE:* ISO recommends that capitalization follow the accepted practice for the language or script in which the information is given.**
  See [20].
- *Basic format for patents (when available online):*
  Name of the invention, by inventor's name. (year, month day). Patent Number [Type of medium]. Available: site/path/file
  See [21].
- *Basic formatfor conference proceedings (published):*
  J. K. Author, "Title of paper," in *Abbreviated Name of Conf.*, City of Conf., Abbrev. State (if given), Country, year, pp. *xxxxxx.*
  See [22].
- *Example for papers presented at conferences (unpublished):*
  See [23].
- *Basic format for patents*:
  J. K. Author, "Title of patent," U.S. Patent *x xxx xxx*, Abbrev. Month, day, year.
  See [24].
- *Basic format for theses (M.S.) and dissertations (Ph.D.):*
  1) J. K. Author, "Title of thesis," M.S. thesis, Abbrev. Dept., Abbrev. Univ., City of Univ., Abbrev. State, year.
  2) J. K. Author, "Title of dissertation," Ph.D. dissertation, Abbrev. Dept., Abbrev. Univ., City of Univ., Abbrev. State, year.

  See [25], [26].
- *Basic format for the most common types of unpublished references:*
  1) J. K. Author, private communication, Abbrev. Month, year.
  2) J. K. Author, "Title of paper," unpublished.
  3) J. K. Author, "Title of paper," to be published.

  See [27]– [29].
- *Basic formats for standards:*
  1) *Title of Standard*, Standard number, date.
  2) *Title of Standard*, Standard number, Corporate author, location, date.

  See [30], [31].
- *Article number in reference examples:*
  See [32], [33].
- *Example when using et al.:*
  See [34].

REFERENCES

[1] G. O. Young, "Synthetic structure of industrial plastics," in *Plastics,* 2nd ed., vol. 3, J. Peters, Ed. New York, NY, USA: McGraw-Hill, 1964, pp. 15–64.

[2] W.-K. Chen, *Linear Networks and Systems.* Belmont, CA, USA: Wadsworth, 1993, pp. 123–135.

[3] J. U. Duncombe, "Infrared navigation—Part I: An assessment of feasibility," *IEEE Trans. Electron Devices*, vol. ED-11, no. 1, pp. 34–39, Jan. 1959, 10.1109/TED.2016.2628402.

[4] E. P. Wigner, "Theory of traveling-wave optical laser," *Phys. Rev*., vol. 134, pp. A635–A646, Dec. 1965.

[5] E. H. Miller, "A note on reflector arrays," *IEEE Trans. Antennas Propagat*., to be published.
[6] E. E. Reber, R. L. Michell, and C. J. Carter, "Oxygen absorption in the earth's atmosphere," Aerospace Corp., Los Angeles, CA, USA, Tech. Rep. TR-0200 (4230-46)-3, Nov. 1988.
[7] J. H. Davis and J. R. Cogdell, "Calibration program for the 16-foot antenna," Elect. Eng. Res. Lab., Univ. Texas, Austin, TX, USA, Tech. Memo. NGL-006-69-3, Nov. 15, 1987.
[8] *Transmission Systems for Communications*, 3rd ed., Western Electric Co., Winston-Salem, NC, USA, 1985, pp. 44–60.
[9] *Motorola Semiconductor Data Manual*, Motorola Semiconductor Products Inc., Phoenix, AZ, USA, 1989.
[10] G. O. Young, "Synthetic structure of industrial plastics," in Plastics, vol. 3, Polymers of Hexadromicon, J. Peters, Ed., 2nd ed. New York, NY, USA: McGraw-Hill, 1964, pp. 15-64. [Online]. Available: http://www.bookref.com.
[11] *The Founders' Constitution*, Philip B. Kurland and Ralph Lerner, eds., Chicago, IL, USA: Univ. Chicago Press, 1987. [Online]. Available: http://press-pubs.uchicago.edu/founders/
[12] The Terahertz Wave eBook. ZOmega Terahertz Corp., 2014. [Online]. Available: http://dl.z-thz.com/eBook/zomega_ebook_pdf_1206_sr.pdf. Accessed on: May 19, 2014.
[13] Philip B. Kurland and Ralph Lerner, eds., *The Founders' Constitution.* Chicago, IL, USA: Univ. of Chicago Press, 1987, Accessed on: Feb. 28, 2010, [Online] Available: http://press-pubs.uchicago.edu/founders/
[14] J. S. Turner, "New directions in communications," *IEEE J. Sel. Areas Commun*., vol. 13, no. 1, pp. 11-23, Jan. 1995.
[15] W. P. Risk, G. S. Kino, and H. J. Shaw, "Fiber-optic frequency shifter using a surface acoustic wave incident at an oblique angle," *Opt. Lett.*, vol. 11, no. 2, pp. 115–117, Feb. 1986.
[16] P. Kopyt *et al.,* "Electric properties of graphene-based conductive layers from DC up to terahertz range," *IEEE THz Sci. Technol.,* to be published. DOI: 10.1109/TTHZ.2016.2544142.
[17] PROCESS Corporation, Boston, MA, USA. Intranets: Internet technologies deployed behind the firewall for corporate productivity. Presented at INET96 Annual Meeting. [Online]. Available: http://home.process.com/Intranets/wp2.htp
[18] R. J. Hijmans and J. van Etten, "Raster: Geographic analysis and modeling with raster data," R Package Version 2.0-12, Jan. 12, 2012. [Online]. Available: http://CRAN.R-project.org/package=raster
[19] Teralyzer. Lytera UG, Kirchhain, Germany [Online]. Available: http://www.lytera.de/Terahertz_THz_Spectroscopy.php?id=home, Accessed on: Jun. 5, 2014
[20] U.S. House. 102nd Congress, 1st Session. (1991, Jan. 11). *H. Con. Res. 1, Sense of the Congress on Approval of Military Action*. [Online]. Available: LEXIS Library: GENFED File: BILLS
[21] Musical toothbrush with mirror, by L.M.R. Brooks. (1992, May 19). Patent D 326 189 [Online]. Available: NEXIS Library: LEXPAT File: DES
[22] D. B. Payne and J. R. Stern, "Wavelength-switched pas- sively coupled single-mode optical network," in *Proc. IOOC-ECOC,* Boston, MA, USA, 1985, pp. 585–590.
[23] D. Ebehard and E. Voges, "Digital single sideband detection for interferometric sensors," presented at the *2nd Int. Conf. Optical Fiber Sensors,* Stuttgart, Germany, Jan. 2-5, 1984.
[24] G. Brandli and M. Dick, "Alternating current fed power supply," U.S. Patent 4 084 217, Nov. 4, 1978.
[25] J. O. Williams, "Narrow-band analyzer," Ph.D. dissertation, Dept. Elect. Eng., Harvard Univ., Cambridge, MA, USA, 1993.
[26] N. Kawasaki, "Parametric study of thermal and chemical nonequilibrium nozzle flow," M.S. thesis, Dept. Electron. Eng., Osaka Univ., Osaka, Japan, 1993.
[27] A. Harrison, private communication, May 1995.
[28] B. Smith, "An approach to graphs of linear forms," unpublished.
[29] A. Brahms, "Representation error for real numbers in binary computer arithmetic," IEEE Computer Group Repository, Paper R-67-85.
[30] IEEE Criteria for Class IE Electric Systems, IEEE Standard 308, 1969.
[31] Letter Symbols for Quantities, ANSI Standard Y10.5-1968.
[32] R. Fardel, M. Nagel, F. Nuesch, T. Lippert, and A. Wokaun, "Fabrication of organic light emitting diode pixels by laser-assisted forward transfer," *Appl. Phys. Lett.*, vol. 91, no. 6, Aug. 2007, Art. no. 061103.
[33] J. Zhang and N. Tansu, "Optical gain and laser characteristics of InGaN quantum wells on ternary InGaN substrates," *IEEE Photon. J.*, vol. 5, no. 2, Apr. 2013, Art. no. 2600111
[34] S. Azodolmolky *et al.*, Experimental demonstration of an impairment aware network planning and operation tool for transparent/translucent optical networks," *J. Lightw. Technol.*, vol. 29, no. 4, pp. 439–448, Sep. 2011.

First A. Author (M'76–SM'81–F'87) and all authors may include biographies. Biographies are often not included in conference-related papers. This author became a Member (M) of IEEE in 1976, a Senior Member (SM) in 1981, and a Fellow (F) in 1987. The first paragraph may contain a place and/or date of birth (list place, then date). Next, the author's educational background is listed. The degrees should be listed with type of degree in what field, which institution, city, state, and country, and year the degree was earned. The author's major field of study should be lower-cased.

The second paragraph uses the pronoun of the person (he or she) and not the author's last name. It lists military and work experience, including summer and fellowship jobs. Job titles are capitalized. The current job must have a location; previous positions may be listed without one. Information concerning previous publications may be included. Try not to list more than three books or published articles. The format for listing publishers of a book within the biography is: title of book (publisher name, year) similar to a reference. Current and previous research interests end the paragraph. The third paragraph begins with the author's title and last name (e.g., Dr. Smith, Prof. Jones, Mr. Kajor, Ms. Hunter). List any memberships in professional societies other than the IEEE. Finally, list any awards and work for IEEE committees and publications. If a photograph is provided, it should be of good quality, and professional-looking. Following are two examples of an author's biography.

Second B. Author was born in Greenwich Village, New York, NY, USA in 1977. He received the B.S. and M.S. degrees in aerospace engineering from the University of Virginia, Charlottesville, in 2001 and the Ph.D. degree in mechanical engineering from Drexel University, Philadelphia, PA, in 2008.

From 2001 to 2004, he was a Research Assistant with the Princeton Plasma Physics Laboratory. Since 2009, he has been an Assistant Professor with the Mechanical Engineering Department, Texas A&M University, College Station. He is the author of three books, more than 150 articles, and more than 70 inventions. His research interests include high-pressure and high-density nonthermal plasma discharge processes and applications, microscale plasma discharges, discharges in liquids, spectroscopic diagnostics, plasma propulsion, and innovation plasma applications. He is an Associate Editor of the journal *Earth, Moon, Planets*, and holds two patents.

Dr. Author was a recipient of the International Association of Geomagnetism and Aeronomy Young Scientist Award for Excellence in 2008, and the IEEE Electromagnetic Compatibility Society Best Symposium Paper Award in 2011.

Third C. Author, Jr. (M'87) received the B.S. degree in mechanical engineering from National Chung Cheng University, Chiayi, Taiwan, in 2004 and the M.S. degree in mechanical engineering from National Tsing Hua University, Hsinchu, Taiwan, in 2006. He is currently pursuing the Ph.D. degree in mechanical engineering at Texas A&M University, College Station, TX, USA.

From 2008 to 2009, he was a Research Assistant with the Institute of Physics, Academia Sinica, Tapei, Taiwan. His research interest includes the development of surface processing and biological/medical treatment techniques using nonthermal atmospheric pressure plasmas, fundamental study of plasma sources, and fabrication of micro- or nanostructured surfaces.

Mr. Author's awards and honors include the Frew Fellowship (Australian Academy of Science), the I. I. Rabi Prize (APS), the European Frequency and Time Forum Award, the Carl Zeiss Research Award, the William F. Meggers Award and the Adolph Lomb Medal (OSA).