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# Galaxy Morphological Classification with Efficient Vision Transformer

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## Abstract

Quantifying the morphology of galaxies has been an important task in astrophysics to understand the formation and evolution of galaxies. In recent years, the data size has been dramatically increasing due to several on-going and upcoming surveys. Labeling and identifying interesting objects for further investigations has been explored by citizen science through the Galaxy Zoo Project and by machine learning in particular with the convolutional neural networks (CNNs). In this work, we explore the usage of Vision Transformer (ViT) for galaxy morphology classification for the first time. We show that ViT could reach competitive results compared with CNNs, and is specifically good at classifying smaller-sized and fainter galaxies. With this promising preliminary result, we believe the ViT network architecture can be an important tool for galaxy morphological classification for the next generation surveys. Our open source, is publicly available at <https://github.com/sliao-mi-luku/Galaxy-Zoo-Classification>

## 1 Introduction

Galaxy visual morphology reveals their intrinsic, structural, and environmental properties. These properties indicate the age of galaxies, galaxy formation history, and interaction with other galaxies[1, 2, 3, 4]. Since the pioneering galaxy classification system by Hubble[5, 6], much of our understanding of galaxy morphological classification relies on human inspection. One of the largest such project was Galaxy Zoo [7, 8]. It harnessed hundreds of thousands of volunteers to classify the morphology of galaxy images from Sloan Digital Sky Survey (SDSS) [9]. This project turned out to be a great success and led to the launch of many similar projects such as Galaxy Zoo 2[10], Galaxy Zoo: Hubble[11], and Galaxy Zoo: CANDELS[12]. Despite the success of these citizen science projects, astronomers still need an automated classification program to provide consistent and precise results while also handling massive amount of data from ongoing [13, 14, 15] or future sky surveys [16, 17, 18].

Machine learning (ML) based methods are well suited for such automated image classification problems, especially the deep learning based methods such as the convolutional neural networks (CNNs). Over the past two decades, several ML techniques have been successfully applied in the tasks of galaxy morphological classification[19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33].

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\*equal contribution

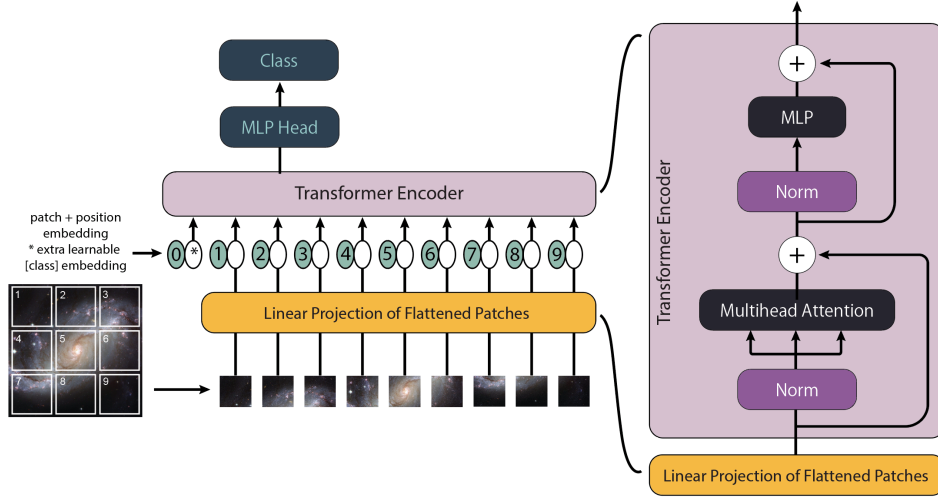


Figure 1: The architecture overview of Vision Transformer. This diagram is adapted from [34].

Recently, Google developed a novel image classification architecture called Vision Transformer (ViT)[34]. The Transformer-like architecture was originally designed to analyze sequential data in Natural Language Processing (NLP)[35]. The key ingredient in Transformer is the parallelizable attention mechanism which enables the neural network to highlight significant pairwise correlations between different elements. Hence, the underlying long-range correlations tend to be more easily captured. This feature led to the great success of Transformers in NLP (e.g. Bert[36], GPT-3[37]), which motivates the development of Vision Transformer to handle image classification tasks (the architecture of ViT is shown in Fig. 1). The process starts with splitting an image into patches with sequential position embeddings. These image patches with an extra learnable embedding (white ellipse with number 0 in Fig. 1) serve as the input sequence. The extra learnable embedding can be used to classify the input image after being updated by pre-trained attention layers. The advantage of ViT is its outperformance over the state-of-the-art CNNs when the number of training data is large enough (around 300M) [34]. This striking property suggests that ViT would be a good galaxy morphological classification candidate due to the rapidly increasing amount of galaxy images for future sky surveys such as the Legacy Survey of Space and Time (LSST [16]), which is expected to observe 20 billion galaxies during its 10-year operation.

This work is the first attempt of applying Vision Transformer on galaxy morphological classification tasks. We use the Linformer model (in Sec. 2), a variant of ViT where the complexity of the attention mechanism is reduced from quadratic to linear (in the size of input patch sequence). Hereafter, we will use ViT as a representation of our Linformer model. We demonstrate in Sec. 3 that the performance of ViT is competitive with the ResNet-50 CNN model with the number of training data being only around a hundred thousand. Additionally, by applying class weights in the loss function, our networks achieve more balanced categorical accuracies over all morphological types compared with previous studies [26]. Finally, we find that ViT models are specifically good at classifying small-sized and faint galaxies, which are the dominant populations for future telescopes that survey deeper in sky. With this promising preliminary result, we believe the Vision Transformer network architecture can be an important tool for galaxy morphological classification.

## 2 Data and Model

### 2.1 Dataset

The galaxy dataset used in this study is based on the Galaxy Zoo 2 Project<sup>2</sup> (GZ2)[38], with the morphological information drawn from the catalog of Hart et al. [39], and the galaxy images

<sup>2</sup><https://data.galaxyzoo.org>

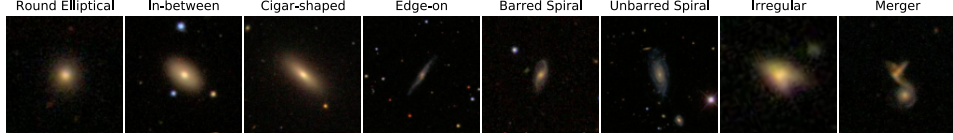


Figure 2: Examples of galaxy images from each of the eight morphological classes.

downloaded from kaggle<sup>3</sup>. The size of each image is  $424 \times 424 \times 3$  pixels, with the color channels corresponding the  $g, r, i$  filters of the SDSS [9].

The morphological classification labels of galaxies can be derived by applying thresholds on a series of voting questions answered by participants in GZ2. Following the criteria suggested in [38, 40], we construct a clean galaxy dataset with eight distinct classes and label them from 0~7 in the order of: round elliptical, in-between elliptical, cigar-shaped elliptical, edge-on, barred spiral, unbarred spiral, irregular and merger galaxies. Fig. 2 shows example galaxy images of each morphological class.

Our final baseline dataset consists of 155,951 images, which is more than five times larger compared with previous machine learning studies on galaxy classification problems with the GZ2 dataset [26, 40, 41].

We split the data into 64% train set, 16% validation set, and 20% test set. We crop images into  $224 \times 224 \times 3$ , and use data augmentation techniques by flipping and rotating the images. We normalize pixel values in each color channel by the mean ( $[0.094, 0.0815, 0.063]$ ) and the standard deviation ( $[0.1303, 0.11, 0.0913]$ ) obtained from the dataset.

## 2.2 Vision Transformer model

We use Linformer as our Vision Transformer model[42]. The main feature of Linformer is its linear ( $\mathcal{O}(n)$  where  $n$  is the size of the input patch sequence) attention complexity instead of the quadratic complexity ( $\mathcal{O}(n^2)$ ) in the original ViT. This reduction of complexity is essential particularly for lowering the computational cost. This efficient training originates from approximating the original attention matrix by a low-rank matrix. The original attention matrix is defined as

$$Attention \equiv \overbrace{\text{softmax}\left(\frac{QK^T}{\sqrt{d}}\right)}^P V, \quad Q = XW_Q, K = XW_K, V = XW_V \quad (1)$$

where  $X$  is the embedded input sequence and  $W_Q, W_K, W_V$  are three learnable weight matrices. Their respective dimensions are  $X \in \mathbb{R}^{n \times d}, W_Q, W_K, W_V \in \mathbb{R}^{d \times d}$  where  $n$  is the size of the patch sequence and  $d$  is the embedding dimension. Naively,  $V$  can be viewed as the overall weighting factor for each element in the sequence  $X$ , whereas  $P$  weights the dominant pairwise correlation between each elements. The computation complexity of  $P$  ( $\mathcal{O}(n^2)$ ) is the main efficiency bottleneck in Transformer-like models. To reduce the rank of  $P$ , Linformer introduced two  $(k \times n)$ -dimensional linear projection matrices  $E_K, E_V$  where  $n \gg k$ . The modified  $\tilde{K}, \tilde{V}$  matrices are  $\tilde{K} = E_K X W_K, \tilde{V} = E_V X W_V$ . Consequently, the rank of  $P$  is reduced to  $n \times k$ . Since  $n \gg k$ , the complexity drops to  $\mathcal{O}(n)$ .

Our model has 2,785,416 trainable parameters. We apply  $patch\ size = 28, depth = 12, hidden\ dim = 128, k-dim = 64, num\ head = 8, lr = 3 \times 10^{-4}, step\ size = 5, gamma = 0.9$  and train our transformer for 200 epochs. We use two different loss functions 1) regular cross-entropy without weights 2) cross-entropy with class weights of (0.19, 0.21, 0.98, 0.38, 0.53, 0.66, 1.81, 3.23).

## 3 Result

We present our best overall accuracy and individual class accuracy from our Linformer models. Due to the intrinsic imbalance in different categories, categorical accuracy is another important performance indicator. Our best overall accuracy is 80.55%, whereas the best individual class accuracy achieved

<sup>3</sup><https://www.kaggle.com/jaimetriczk/galaxy-zoo-2-images>

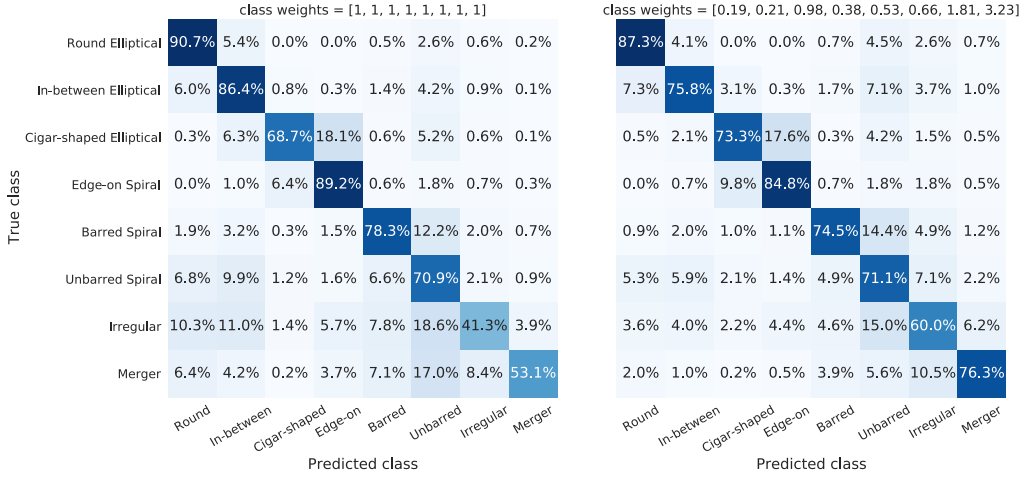


Figure 3: Confusion matrices of the ViT network predictions on the test set, with equal (left) and tuned (right) class weights applied on the loss functions during the training phases.

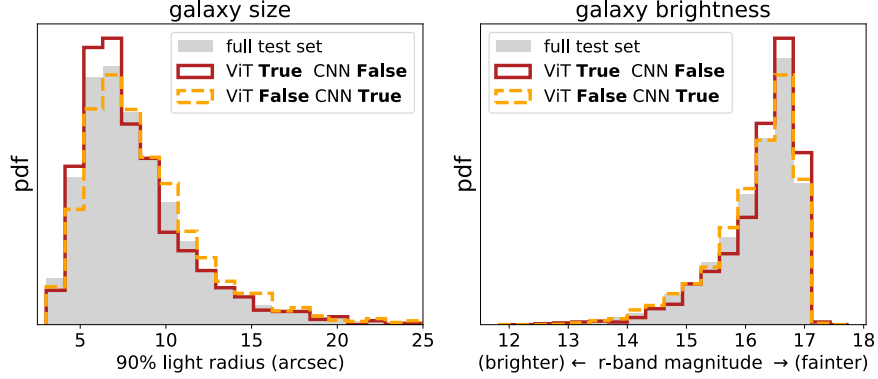


Figure 4: Probability density functions of galaxy size and brightness for the full test set (gray). The red / orange histograms show sub-samples that are classified correctly with ViT / ResNet but are misclassified with ResNet / ViT.

in our weighted-cross entropy Linformer is over 60% in each class (the overall accuracy is 77.42%). All their individual class accuracy results are shown in the confusion matrix (Fig. 3).

We use ResNet-50 as a baseline CNN model to compare with our Linformer models. The best accuracy obtained in ResNet-50 is 85.12%. While our ViT models do not outperform CNN over the entire sample, we explore cases which are correctly classified by one network but failed by the other (see red v.s. orange histograms in Fig. 4). We find that ViT reaches higher classification accuracy in classifying smaller and fainter galaxies which are more challenging to classify since the image quality of these samples are noisier. A possible reasoning for ViT's better performance on fainter and smaller galaxies is that these galaxies dominate the entire dataset and ViT models tend to outperform CNN when more training samples are available[34].

## 4 Discussion and Future work

We have shown promising initial results of applying Linformer, an efficient transformer model, for the task of galaxy morphological classification. We show that our ViT models 1) achieve competitive results compared to the state-of-the-art CNNs, 2) reach more balanced categorical accuracy compared with previous works with tuned class weights applied in the loss function when training, and 3) performs specifically well in classifying smaller-sized and fainter galaxies.

Besides supervised learning, there are many potential applications related to Vision Transformer that could be helpful for future astronomical surveys, such as applying self-supervised learning techniques (e.g. DINO [43]) to automatically classify images in the big-data epoch when human power for labeling data becomes impossible.

Over the next 10 years, the Rubin Observatory LSST is expected to retrieve 20 billion (15 PB) galaxy images with unprecedented sensitivity to observed  $\sim 10$  orders of magnitude fainter galaxies compared with the GZ2 dataset used in this study [44]. Our results therefore demonstrate the great potential of ViT’s applications on analyzing astronomical images in the era when much larger and deeper datasets become available, allowing us to study in greater detail on the physics of galaxies and the Universe.

## 5 Broader Impact

We hope the astronomy community would benefit from Vision Transformer. We expect no specific unethical issues that would be related to galaxy morphology classification project.

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## References

- [1] A. Dressler. Galaxy morphology in rich clusters: implications for the formation and evolution of galaxies. *ApJ*, 236:351–365, March 1980.
- [2] Iskra Strateva, Željko Ivezić, Gillian R. Knapp, Vijay K. Narayanan, Michael A. Strauss, James E. Gunn, Robert H. Lupton, David Schlegel, Neta A. Bahcall, Jon Brinkmann, Robert J. Brunner, Tamás Budavári, István Csabai, Francisco Javier Castander, Mamoru Doi, Masataka Fukugita, Zsuzsanna Győry, Masaru Hamabe, Greg Hennessy, Takashi Ichikawa, Peter Z. Kunszt, Don Q. Lamb, Timothy A. McKay, Sadanori Okamura, Judith Racusin, Maki Sekiguchi, Donald P. Schneider, Kazuhiro Shimasaku, and Donald York. Color Separation of Galaxy Types in the Sloan Digital Sky Survey Imaging Data. *AJ*, 122(4):1861–1874, October 2001.
- [3] Shiyin Shen, H. J. Mo, Simon D. M. White, Michael R. Blanton, Guinevere Kauffmann, Wolfgang Voges, J. Brinkmann, and Istvan Csabai. The size distribution of galaxies in the Sloan Digital Sky Survey. *MNRAS*, 343(3):978–994, August 2003.
- [4] Masataka Fukugita, Osamu Nakamura, Sadanori Okamura, Naoki Yasuda, John C. Barentine, Jon Brinkmann, James E. Gunn, Mike Harvanek, Takashi Ichikawa, Robert H. Lupton, Donald P. Schneider, Michael A. Strauss, and Donald G. York. A catalog of morphologically classified galaxies from the sloan digital sky survey: North equatorial region. *The Astronomical Journal*, 134(2):579–593, jun 2007.
- [5] E. P. Hubble. Extragalactic nebulae. *ApJ*, 64:321–369, December 1926.
- [6] E. P. Hubble. *Realm of the Nebulae*. 1936.
- [7] Chris J. Lintott, Kevin Schawinski, Anže Slosar, Kate Land, Steven Bamford, Daniel Thomas, M. Jordan Raddick, Robert C. Nichol, Alex Szalay, Dan Andreescu, Phil Murray, and Jan Vandenberg. Galaxy Zoo: morphologies derived from visual inspection of galaxies from the Sloan Digital Sky Survey\*. *Monthly Notices of the Royal Astronomical Society*, 389(3):1179–1189, 09 2008.
- [8] Chris Lintott, Kevin Schawinski, Steven Bamford, Anže Slosar, Kate Land, Daniel Thomas, Edd Edmondson, Karen Masters, Robert C. Nichol, M. Jordan Raddick, Alex Szalay, Dan Andreescu, Phil Murray, and Jan Vandenberg. Galaxy Zoo 1: data release of morphological classifications for nearly 900 000 galaxies. *MNRAS*, 410(1):166–178, January 2011.
- [9] Donald G. York, J. Adelman, Jr. Anderson, John E., Scott F. Anderson, James Annis, Neta A. Bahcall, J. A. Bakken, Robert Barkhouser, Steven Bastian, Eileen Berman, William N. Boroski,

- Steve Bracker, Charlie Briegel, John W. Briggs, J. Brinkmann, Robert Brunner, Scott Burles, Larry Carey, Michael A. Carr, Francisco J. Castander, Bing Chen, Patrick L. Colestock, A. J. Connolly, J. H. Crocker, István Csabai, Paul C. Czarapata, John Eric Davis, Mamoru Doi, Tom Dombeck, Daniel Eisenstein, Nancy Ellman, Brian R. Elms, Michael L. Evans, Xiaohui Fan, Glenn R. Federwitz, Larry Fiacelli, Scott Friedman, Joshua A. Frieman, Masataka Fukugita, Bruce Gillespie, James E. Gunn, Vijay K. Gurbani, Ernst de Haas, Merle Haldeman, Frederick H. Harris, J. Hayes, Timothy M. Heckman, G. S. Hennessy, Robert B. Hindsley, Scott Holm, Donald J. Holmgren, Chi-hao Huang, Charles Hull, Don Husby, Shin-Ichi Ichikawa, Takashi Ichikawa, Željko Ivezić, Stephen Kent, Rita S. J. Kim, E. Kinney, Mark Klaene, A. N. Kleinman, S. Kleinman, G. R. Knapp, John Korienek, Richard G. Kron, Peter Z. Kunszt, D. Q. Lamb, B. Lee, R. French Leger, Siriluk Limmongkol, Carl Lindenmeyer, Daniel C. Long, Craig Loomis, Jon Loveday, Rich Lucinio, Robert H. Lupton, Bryan MacKinnon, Edward J. Mannery, P. M. Mantsch, Bruce Margon, Peregrine McGehee, Timothy A. McKay, Avery Meiksin, Aronne Merelli, David G. Monet, Jeffrey A. Munn, Vijay K. Narayanan, Thomas Nash, Eric Neilsen, Rich Neswold, Heidi Jo Newberg, R. C. Nichol, Tom Nicinski, Mario Nonino, Norio Okada, Sadanori Okamura, Jeremiah P. Ostriker, Russell Owen, A. George Pauls, John Peoples, R. L. Peterson, Donald Petravick, Jeffrey R. Pier, Adrian Pope, Ruth Pordes, Angela Prosapio, Ron Rechenmacher, Thomas R. Quinn, Gordon T. Richards, Michael W. Richmond, Claudio H. Rivetta, Constance M. Rockosi, Kurt Ruthmansdorfer, Dale Sandford, David J. Schlegel, Donald P. Schneider, Maki Sekiguchi, Gary Sergey, Kazuhiro Shimasaku, Walter A. Siegmund, Stephen Smee, J. Allyn Smith, S. Snedden, R. Stone, Chris Stoughton, Michael A. Strauss, Christopher Stubbs, Mark SubbaRao, Alexander S. Szalay, Istvan Szapudi, Gyula P. Szokoly, Anirudda R. Thakar, Christy Tremonti, Douglas L. Tucker, Alan Uomoto, Dan Vanden Berk, Michael S. Vogeley, Patrick Waddell, Shu-i. Wang, Masaru Watanabe, David H. Weinberg, Brian Yanny, Naoki Yasuda, and SDSS Collaboration. The Sloan Digital Sky Survey: Technical Summary. *AJ*, 120(3):1579–1587, September 2000.
- [10] Kyle W. Willett, Chris J. Lintott, Steven P. Bamford, Karen L. Masters, Brooke D. Simmons, Kevin R. V. Casteels, Edward M. Edmondson, Lucy F. Fortson, Sugata Kaviraj, William C. Keel, Thomas Melvin, Robert C. Nichol, M. Jordan Raddick, Kevin Schawinski, Robert J. Simpson, Ramin A. Skibba, Arfon M. Smith, and Daniel Thomas. Galaxy Zoo 2: detailed morphological classifications for 304 122 galaxies from the Sloan Digital Sky Survey. *MNRAS*, 435(4):2835–2860, November 2013.
- [11] Kyle W. Willett, Melanie A. Galloway, Steven P. Bamford, Chris J. Lintott, Karen L. Masters, Claudia Scarlata, B. D. Simmons, Melanie Beck, Carolin N. Cardamone, Edmond Cheung, Edward M. Edmondson, Lucy F. Fortson, Roger L. Griffith, Boris Häußler, Anna Han, Ross Hart, Thomas Melvin, Michael Parrish, Kevin Schawinski, R. J. Smethurst, and Arfon M. Smith. Galaxy Zoo: morphological classifications for 120 000 galaxies in HST legacy imaging. *MNRAS*, 464(4):4176–4203, February 2017.
- [12] B. D. Simmons, Chris Lintott, Kyle W. Willett, Karen L. Masters, Jeyhan S. Kartaltepe, Boris Häußler, Sugata Kaviraj, Coleman Krawczyk, S. J. Kruk, Daniel H. McIntosh, R. J. Smethurst, Robert C. Nichol, Claudia Scarlata, Kevin Schawinski, Christopher J. Conselice, Omar Almaini, Henry C. Ferguson, Lucy Fortson, William Hartley, Dale Kocevski, Anton M. Koekemoer, Alice Mortlock, Jeffrey A. Newman, Steven P. Bamford, N. A. Grogan, Ray A. Lucas, Nimish P. Hathi, Elizabeth McGrath, Michael Peth, Janine Pforr, Zachary Rizer, Stijn Wuyts, Guillermo Barro, Eric F. Bell, Marco Castellano, Tomas Dahlen, Avishai Dekel, Jamie Ownsworth, Sandra M. Faber, Steven L. Finkelstein, Adriano Fontana, Audrey Galametz, Ruth Grützbauch, David Koo, Jennifer Lotz, Bahram Mobasher, Mark Mozena, Mara Salvato, and Tommy Wiklund. Galaxy Zoo: quantitative visual morphological classifications for 48 000 galaxies from CANDELS. *MNRAS*, 464(4):4420–4447, February 2017.
- [13] DES Collaboration, T. M. C. Abbott, M. Aguena, A. Alarcon, S. Allam, O. Alves, A. Amon, F. Andrade-Oliveira, J. Annis, S. Avila, D. Bacon, E. Baxter, K. Bechtol, M. R. Becker, G. M. Bernstein, S. Bhargava, S. Birrer, J. Blazek, A. Brandao-Souza, S. L. Bridle, D. Brooks, E. Buckley-Geer, D. L. Burke, H. Camacho, A. Campos, A. Carnero Rosell, M. Carrasco Kind, J. Carretero, F. J. Castander, R. Cawthon, C. Chang, A. Chen, R. Chen, A. Choi, C. Conselice, J. Cordero, M. Costanzi, M. Crocce, L. N. da Costa, M. E. da Silva Pereira, C. Davis, T. M. Davis, J. De Vicente, J. DeRose, S. Desai, E. Di Valentino, H. T. Diehl, J. P. Dietrich, S. Dodelson, P. Doel, C. Dux, A. Drlica-Wagner, K. Eckert, T. F. Eifler, F. Elsner, J. Elvin-Poole, S. Everett, A. E. Evrard, X. Fang, A. Farahi, E. Fernandez, I. Ferrero, A. Ferté,

- P. Fosalba, O. Friedrich, J. Frieman, J. García-Bellido, M. Gatti, E. Gaztanaga, D. W. Gerdes, T. Giannantonio, G. Giannini, D. Gruen, R. A. Gruendl, J. Gschwend, G. Gutierrez, I. Harrison, W. G. Hartley, K. Herner, S. R. Hinton, D. L. Hollowood, K. Honscheid, B. Hoyle, E. M. Huff, D. Huterer, B. Jain, D. J. James, M. Jarvis, N. Jeffrey, T. Jeltema, A. Kovacs, E. Krause, R. Kron, K. Kuehn, N. Kuropatkin, O. Lahav, P. F. Leget, P. Lemos, A. R. Liddle, C. Lidman, M. Lima, H. Lin, N. MacCrann, M. A. G. Maia, J. L. Marshall, P. Martini, J. McCullough, P. Melchior, J. Mena-Fernández, F. Menanteau, R. Miquel, J. J. Mohr, R. Morgan, J. Muir, J. Myles, S. Nadathur, A. Navarro-Alsina, R. C. Nichol, R. L. C. Ogando, Y. Omori, A. Palmese, S. Pandey, Y. Park, F. Paz-Chinchón, D. Petravick, A. Pieres, A. A. Plazas Malagón, A. Porredon, J. Prat, M. Raveri, M. Rodríguez-Monroy, R. P. Rollins, A. K. Romer, A. Roodman, R. Rosenfeld, A. J. Ross, E. S. Rykoff, S. Samuroff, C. Sánchez, E. Sanchez, J. Sanchez, D. Sanchez Cid, V. Scarpine, M. Schubnell, D. Scolnic, L. F. Secco, S. Serrano, I. Sevilla-Noarbe, E. Sheldon, T. Shin, M. Smith, M. Soares-Santos, E. Suchyta, M. E. C. Swanson, M. Tabbutt, G. Tarle, D. Thomas, C. To, A. Troja, M. A. Troxel, D. L. Tucker, I. Tutusaus, T. N. Varga, A. R. Walker, N. Weaverdyck, J. Weller, B. Yanny, B. Yin, Y. Zhang, and J. Zuntz. Dark Energy Survey Year 3 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing. *arXiv e-prints*, page arXiv:2105.13549, May 2021.
- [14] Jelte T. A. de Jong, Gijs A. Verdoes Kleijn, Konrad H. Kuijken, and Edwin A. Valentijn. The Kilo-Degree Survey. *Experimental Astronomy*, 35(1-2):25–44, January 2013.
- [15] Chiaki Hikage, Masamune Oguri, Takashi Hamana, Surhud More, Rachel Mandelbaum, Masahiro Takada, Fabian Köhlinger, Hironao Miyatake, Atsushi J. Nishizawa, Hiroaki Aihara, Robert Armstrong, James Bosch, Jean Coupon, Anne Ducoat, Paul Ho, Bau-Ching Hsieh, Yutaka Komiyama, François Lanusse, Alexie Leauthaud, Robert H. Lupton, Elinor Medezinski, Sogo Mineo, Shoken Miyama, Satoshi Miyazaki, Ryoma Murata, Hitoshi Murayama, Masato Shirasaki, Cristóbal Sifón, Melanie Simet, Joshua Speagle, David N. Spergel, Michael A. Strauss, Naoshi Sugiyama, Masayuki Tanaka, Yousuke Utsumi, Shiang-Yu Wang, and Yoshihiko Yamada. Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam first-year data. *PASJ*, 71(2):43, April 2019.
- [16] LSST Science Collaboration, Paul A. Abell, Julius Allison, Scott F. Anderson, John R. Andrew, J. Roger P. Angel, Lee Armus, David Arnett, S. J. Asztalos, Tim S. Axelrod, Stephen Bailey, D. R. Ballantyne, Justin R. Bankert, Wayne A. Barkhouse, Jeffrey D. Barr, L. Felipe Barrientos, Aaron J. Barth, James G. Bartlett, Andrew C. Becker, Jacek Becla, Timothy C. Beers, Joseph P. Bernstein, Rahul Biswas, Michael R. Blanton, Joshua S. Bloom, John J. Bochanski, Pat Boeshaar, Kirk D. Borne, Marusa Bradac, W. N. Brandt, Carrie R. Bridge, Michael E. Brown, Robert A. Brunner, James S. Bullock, Adam J. Burgasser, James H. Burge, David L. Burke, Phillip A. Cargile, Srinivasan Chandrasekharan, George Chartas, Steven R. Chesley, You-Hua Chu, David Cinabro, Mark W. Claire, Charles F. Claver, Douglas Clowe, A. J. Connolly, Kem H. Cook, Jeff Cooke, Asantha Cooray, Kevin R. Covey, Christopher S. Culliton, Roelof de Jong, Willem H. de Vries, Victor P. Debattista, Francisco Delgado, Ian P. Dell’Antonio, Saurav Dhital, Rosanne Di Stefano, Mark Dickinson, Benjamin Dilday, S. G. Djorgovski, Gregory Dobler, Ciro Donalek, Gregory Dubois-Felsmann, Josef Durech, Ardis Eliasdottir, Michael Eracleous, Laurent Eyer, Emilio E. Falco, Xiaohui Fan, Christopher D. Fassnacht, Harry C. Ferguson, Yanga R. Fernandez, Brian D. Fields, Douglas Finkbeiner, Eduardo E. Figueroa, Derek B. Fox, Harold Francke, James S. Frank, Josh Frieman, Sebastien Fromenteau, Muhammad Furqan, Gaspar Galaz, A. Gal-Yam, Peter Garnavich, Eric Gawiser, John Geary, Perry Gee, Robert R. Gibson, Kirk Gilmore, Emily A. Grace, Richard F. Green, William J. Gressler, Carl J. Grillmair, Salman Habib, J. S. Haggerty, Mario Hamuy, Alan W. Harris, Suzanne L. Hawley, Alan F. Heavens, Leslie Hebb, Todd J. Henry, Edward Hileman, Eric J. Hilton, Keri Hoadley, J. B. Holberg, Matt J. Holman, Steve B. Howell, Leopoldo Infante, Zeljko Ivezic, Suzanne H. Jacoby, Bhuvnesh Jain, R. Jedicke, M. James Jee, J. Garrett Jernigan, Saurabh W. Jha, Kathryn V. Johnston, R. Lynne Jones, Mario Juric, Mikko Kaasalainen, Styliani, Kafka, Steven M. Kahn, Nathan A. Kaib, Jason Kalirai, Jeff Kantor, Mansi M. Kasliwal, Charles R. Keeton, Richard Kessler, Zoran Knezevic, Adam Kowalski, Victor L. Krabbendam, K. Simon Krughoff, Shrinivas Kulkarni, Stephen Kuhlman, Mark Lacy, Sebastien Lepine, Ming Liang, Amy Lien, Paulina Lira, Knox S. Long, Suzanne Lorenz, Jennifer M. Lotz, R. H. Lupton, Julie Lutz, Lucas M. Macri, Ashish A. Mahabal, Rachel Mandelbaum, Phil Marshall, Morgan May, Peregrine M. McGehee, Brian T. Meadows, Alan Meert, Andrea Milani, Christopher J. Miller, Michelle Miller, David Mills, Dante Minniti, David Monet, Anjum S. Mukadam, Ehud Nakar, Douglas R.



- Neill, Jeffrey A. Newman, Sergei Nikolaev, Martin Nordby, Paul O'Connor, Masamune Oguri, John Oliver, Scot S. Olivier, Julia K. Olsen, Knut Olsen, Edward W. Olszewski, Hakeem Oluseyi, Nelson D. Padilla, Alex Parker, Joshua Pepper, John R. Peterson, Catherine Petry, Philip A. Pinto, James L. Pizagno, Bogdan Popescu, Andrej Prsa, Veljko Radcka, M. Jordan Raddick, Andrew Rasmussen, Arne Rau, Jeonghee Rho, James E. Rhoads, Gordon T. Richards, Stephen T. Ridgway, Brant E. Robertson, Rok Roskar, Abhijit Saha, Ata Sarajedini, Evan Scannapieco, Terry Schalk, Rafe Schindler, Samuel Schmidt, Sarah Schmidt, Donald P. Schneider, German Schumacher, Ryan Scranton, Jacques Sebag, Lynn G. Seppala, Ohad Shemmer, Joshua D. Simon, M. Sivertz, Howard A. Smith, J. Allyn Smith, Nathan Smith, Anna H. Spitz, Adam Stanford, Keivan G. Stassun, Jay Strader, Michael A. Strauss, Christopher W. Stubbs, Donald W. Sweeney, Alex Szalay, Paula Szkody, Masahiro Takada, Paul Thorman, David E. Trilling, Virginia Trimble, Anthony Tyson, Richard Van Berg, Daniel Vanden Berk, Jake VanderPlas, Licia Verde, Bojan Vrsnak, Lucianne M. Walkowicz, Benjamin D. Wandelt, Sheng Wang, Yun Wang, Michael Warner, Risa H. Wechsler, Andrew A. West, Oliver Wiecha, Benjamin F. Williams, Beth Willman, David Wittman, Sidney C. Wolff, W. Michael Wood-Vasey, Przemek Wozniak, Patrick Young, Andrew Zentner, and Hu Zhan. *LSST Science Book*, Version 2.0. *arXiv e-prints*, page arXiv:0912.0201, December 2009.
- [17] J. Amiaux, R. Scaramella, Y. Mellier, B. Altieri, C. Burigana, Antonio Da Silva, P. Gomez, J. Hoar, R. Laureijs, E. Maiorano, D. Magalhães Oliveira, F. Renk, G. Saavedra Criado, I. Tereno, J. L. Auguères, J. Brinchmann, M. Cropper, L. Duvet, A. Ealet, P. Franzetti, B. Garilli, P. Gondoin, L. Guzzo, H. Hoekstra, R. Holmes, K. Jahnke, T. Kitching, M. Meneghetti, W. Percival, and S. Warren. Euclid mission: building of a reference survey. In Mark C. Clampin, Giovanni G. Fazio, Howard A. MacEwen, and Jr. Oschmann, Jacobus M., editors, *Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave*, volume 8442 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 84420Z, September 2012.
  - [18] D. Spergel, N. Gehrels, C. Baltay, D. Bennett, J. Breckinridge, M. Donahue, A. Dressler, B. S. Gaudi, T. Greene, O. Guyon, C. Hirata, J. Kalirai, N. J. Kasdin, B. Macintosh, W. Moos, S. Perlmutter, M. Postman, B. Rauscher, J. Rhodes, Y. Wang, D. Weinberg, D. Benford, M. Hudson, W. S. Jeong, Y. Mellier, W. Traub, T. Yamada, P. Capak, J. Colbert, D. Masters, M. Penny, D. Savransky, D. Stern, N. Zimmerman, R. Barry, L. Bartusek, K. Carpenter, E. Cheng, D. Content, F. Dekens, R. Demers, K. Grady, C. Jackson, G. Kuan, J. Kruk, M. Melton, B. Nemati, B. Parvin, I. Poberezhskiy, C. Peddie, J. Ruffa, J. K. Wallace, A. Whipple, E. Wollack, and F. Zhao. Wide-Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report. *arXiv e-prints*, page arXiv:1503.03757, March 2015.
  - [19] Adam Gauci, Kristian Zarb Adami, and John Abela. Machine Learning for Galaxy Morphology Classification. *arXiv e-prints*, page arXiv:1005.0390, May 2010.
  - [20] Sander Dieleman, Kyle W. Willett, and Joni Dambre. Rotation-invariant convolutional neural networks for galaxy morphology prediction. *Monthly Notices of the Royal Astronomical Society*, 450(2):1441–1459, 04 2015.
  - [21] P. H. Barchi, F. G. da Costa, R. Sautter, T. C. Moura, D. H. Stalder, R. R. Rosa, and R. R. de Carvalho. Improving galaxy morphology with machine learning. *arXiv e-prints*, page arXiv:1705.06818, May 2017.
  - [22] D. Tuccillo, M. Huertas-Company, E. Decencièrre, and S. Velasco-Forero. Deep learning for studies of galaxy morphology. In Massimo Brescia, S. G. Djorgovski, Eric D. Feigelson, Giuseppe Longo, and Stefano Cavuoti, editors, *Astroinformatics*, volume 325, pages 191–196, June 2017.
  - [23] Melanie R. Beck, Claudia Scarlata, Lucy F. Fortson, Chris J. Lintott, B. D. Simmons, Melanie A. Galloway, Kyle W. Willett, Hugh Dickinson, Karen L. Masters, Philip J. Marshall, and Darryl Wright. Integrating human and machine intelligence in galaxy morphology classification tasks. *MNRAS*, 476(4):5516–5534, June 2018.
  - [24] Nour Eldeen Khalifa, Mohamed Hamed Taha, Aboul Ella Hassanien, and Ibrahim Selim. Deep galaxy v2: Robust deep convolutional neural networks for galaxy morphology classifications. In *2018 International Conference on Computing Sciences and Engineering (ICCSE)*, pages 1–6, 2018.



- [25] H Domínguez Sánchez, M Huertas-Company, M Bernardi, D Tuccillo, and J L Fischer. Improving galaxy morphologies for SDSS with Deep Learning. *Monthly Notices of the Royal Astronomical Society*, 476(3):3661–3676, 02 2018.
- [26] JM Dai and J Tong. Galaxy morphology classification with deep convolutional neural networks. arxiv e-prints. *arXiv preprint arXiv:1807.10406*, 2018.
- [27] Alex Hocking, James E. Geach, Yi Sun, and Neil Davey. An automatic taxonomy of galaxy morphology using unsupervised machine learning. *MNRAS*, 473(1):1108–1129, January 2018.
- [28] Asad Khan, EA Huerta, Sibow Wang, Robert Gruendl, Elise Jennings, and Huihuo Zheng. Deep learning at scale for the construction of galaxy catalogs in the dark energy survey. *Physics Letters B*, 795:248–258, 2019.
- [29] Xiao-Pan Zhu, Jia-Ming Dai, Chun-Jiang Bian, Yu Chen, Shi Chen, and Chen Hu. Galaxy morphology classification with deep convolutional neural networks. *Ap&SS*, 364(4):55, April 2019.
- [30] P. H. Barchi, R. R. de Carvalho, R. R. Rosa, R. A. Sautter, M. Soares-Santos, B. A. D. Marques, E. Clua, T. S. Gonçalves, C. de Sá-Freitas, and T. C. Moura. Machine and Deep Learning applied to galaxy morphology - A comparative study. *Astronomy and Computing*, 30:100334, January 2020.
- [31] Ting-Yun Cheng, Christopher J. Conselice, Alfonso Aragón-Salamanca, Nan Li, Asa F. L. Bluck, Will G. Hartley, James Annis, David Brooks, Peter Doel, Juan García-Bellido, David J. James, Kyler Kuehn, Nikolay Kuropatkin, Mathew Smith, Flavia Sobreira, and Gregory Tarle. Optimizing automatic morphological classification of galaxies with machine learning and deep learning using Dark Energy Survey imaging. *MNRAS*, 493(3):4209–4228, April 2020.
- [32] Ting-Yun Cheng, Marc Huertas-Company, Christopher J. Conselice, Alfonso Aragón-Salamanca, Brant E. Robertson, and Nesar Ramachandra. Beyond the hubble sequence - exploring galaxy morphology with unsupervised machine learning. *MNRAS*, 503(3):4446–4465, May 2021.
- [33] Moonzarin Reza. Galaxy morphology classification using automated machine learning. *Astronomy and Computing*, 37:100492, October 2021.
- [34] Alexey Dosovitskiy, Lucas Beyer, Alexander Kolesnikov, Dirk Weissenborn, Xiaohua Zhai, Thomas Unterthiner, Mostafa Dehghani, Matthias Minderer, Georg Heigold, Sylvain Gelly, et al. An image is worth 16x16 words: Transformers for image recognition at scale. *arXiv preprint arXiv:2010.11929*, 2020.
- [35] Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N Gomez, Łukasz Kaiser, and Illia Polosukhin. Attention is all you need. In *Advances in neural information processing systems*, pages 5998–6008, 2017.
- [36] Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. *arXiv e-prints*, page arXiv:1810.04805, October 2018.
- [37] Tom B Brown, Benjamin Mann, Nick Ryder, Melanie Subbiah, Jared Kaplan, Prafulla Dhariwal, Arvind Neelakantan, Pranav Shyam, Girish Sastry, Amanda Askell, et al. Language models are few-shot learners. *arXiv preprint arXiv:2005.14165*, 2020.
- [38] Kyle W. Willett, Chris J. Lintott, Steven P. Bamford, Karen L. Masters, Brooke D. Simmons, Kevin R. V. Casteels, Edward M. Edmondson, Lucy F. Fortson, Sugata Kaviraj, William C. Keel, Thomas Melvin, Robert C. Nichol, M. Jordan Raddick, Kevin Schawinski, Robert J. Simpson, Ramin A. Skibba, Arfon M. Smith, and Daniel Thomas. Galaxy Zoo 2: detailed morphological classifications for 304 122 galaxies from the Sloan Digital Sky Survey. *MNRAS*, 435(4):2835–2860, November 2013.
- [39] Ross E. Hart, Steven P. Bamford, Kyle W. Willett, Karen L. Masters, Carolin Cardamone, Chris J. Lintott, Robert J. Mackay, Robert C. Nichol, Christopher K. Rosslove, Brooke D. Simmons, and Rebecca J. Smethurst. Galaxy Zoo: comparing the demographics of spiral arm number and a new method for correcting redshift bias. *MNRAS*, 461(4):3663–3682, October 2016.
- [40] Shreyas Kalvankar, Hrushikesh Pandit, and Pranav Parwate. Galaxy Morphology Classification using EfficientNet Architectures. *arXiv e-prints*, page arXiv:2008.13611, August 2020.

- [41] Raghav Gupta, P. K. Srijith, and Shantanu Desai. Galaxy Morphology Classification using Neural Ordinary Differential Equations. *arXiv e-prints*, page arXiv:2012.07735, December 2020.
- [42] Sinong Wang, Belinda Z Li, Madian Khabsa, Han Fang, and Hao Ma. Linformer: Self-attention with linear complexity. *arXiv preprint arXiv:2006.04768*, 2020.
- [43] Mathilde Caron, Hugo Touvron, Ishan Misra, Hervé Jégou, Julien Mairal, Piotr Bojanowski, and Armand Joulin. Emerging properties in self-supervised vision transformers. *arXiv preprint arXiv:2104.14294*, 2021.
- [44] Željko Ivezić, Steven M. Kahn, J. Anthony Tyson, Bob Abel, Emily Acosta, Robyn Allsman, David Alonso, Yusra AlSayyad, Scott F. Anderson, John Andrew, James Roger P. Angel, George Z. Angeli, Reza Ansari, Pierre Antilogus, Constanza Araujo, Robert Armstrong, Kirk T. Arndt, Pierre Astier, Éric Aubourg, Nicole Auza, Tim S. Axelrod, Deborah J. Bard, Jeff D. Barr, Aurelian Barrau, James G. Bartlett, Amanda E. Bauer, Brian J. Bauman, Sylvain Baumont, Ellen Bechtol, Keith Bechtol, Andrew C. Becker, Jacek Becla, Cristina Beldica, Steve Bellavia, Federica B. Bianco, Rahul Biswas, Guillaume Blanc, Jonathan Blazek, Roger D. Blandford, Josh S. Bloom, Joanne Bogart, Tim W. Bond, Michael T. Booth, Anders W. Borgland, Kirk Borne, James F. Bosch, Dominique Boutigny, Craig A. Brackett, Andrew Bradshaw, William Nielsen Brandt, Michael E. Brown, James S. Bullock, Patricia Burchat, David L. Burke, Gianpiero Cagnoli, Daniel Calabrese, Shawn Callahan, Alice L. Callen, Jeffrey L. Carlin, Erin L. Carlson, Srinivasan Chandrasekharan, Glenaver Charles-Emerson, Steve Chesley, Elliott C. Cheu, Hsin-Fang Chiang, James Chiang, Carol Chirino, Derek Chow, David R. Ciardi, Charles F. Claver, Johann Cohen-Tanugi, Joseph J. Cockrum, Rebecca Coles, Andrew J. Connolly, Kem H. Cook, Asantha Cooray, Kevin R. Covey, Chris Cribbs, Wei Cui, Roc Cutri, Philip N. Daly, Scott F. Daniel, Felipe Daruich, Guillaume Daubard, Greg Daues, William Dawson, Francisco Delgado, Alfred Dellapenna, Robert de Peyster, Miguel de Val-Borro, Seth W. Digel, Peter Doherty, Richard Dubois, Gregory P. Dubois-Felsmann, Josef Durech, Frossie Economou, Tim Eifler, Michael Eracleous, Benjamin L. Emmons, Angelo Fausti Neto, Henry Ferguson, Enrique Figueroa, Merlin Fisher-Levine, Warren Focke, Michael D. Foss, James Frank, Michael D. Freemon, Emmanuel Gangler, Eric Gawiser, John C. Geary, Perry Gee, Marla Geha, Charles J. B. Gessner, Robert R. Gibson, D. Kirk Gilmore, Thomas Glanzman, William Glick, Tatiana Goldina, Daniel A. Goldstein, Iain Goodenow, Melissa L. Graham, William J. Gressler, Philippe Gris, Leanne P. Guy, Augustin Guyonnet, Gunther Haller, Ron Harris, Patrick A. Hascall, Justine Haupt, Fabio Hernandez, Sven Herrmann, Edward Hileman, Joshua Hoblitt, John A. Hodgson, Craig Hogan, James D. Howard, Dajun Huang, Michael E. Huffer, Patrick Ingraham, Walter R. Innes, Suzanne H. Jacoby, Bhuvnesh Jain, Fabrice Jammes, James Jee, Tim Jenness, Garrett Jernigan, Darko Jevremović, Kenneth Johns, Anthony S. Johnson, Margaret W. G. Johnson, R. Lynne Jones, Claire Juramy-Gilles, Mario Jurić, Jason S. Kalirai, Nitya J. Kallivayalil, Bryce Kalmbach, Jeffrey P. Kantor, Pierre Karst, Mansi M. Kasliwal, Heather Kelly, Richard Kessler, Veronica Kinnison, David Kirkby, Lloyd Knox, Ivan V. Kotov, Victor L. Krabbendam, K. Simon Krughoff, Petr Kubánek, John Kuczewski, Shri Kulkarni, John Ku, Nadine R. Kurita, Craig S. Lage, Ron Lambert, Travis Lange, J. Brian Langton, Laurent Le Guillou, Deborah Levine, Ming Liang, Kian-Tat Lim, Chris J. Lintott, Kevin E. Long, Margaux Lopez, Paul J. Lotz, Robert H. Lupton, Nate B. Lust, Lauren A. MacArthur, Ashish Mahabal, Rachel Mandelbaum, Thomas W. Markiewicz, Darren S. Marsh, Philip J. Marshall, Stuart Marshall, Morgan May, Robert McKercher, Michelle McQueen, Joshua Meyers, Myriam Migliore, Michelle Miller, David J. Mills, Connor Miraval, Joachim Moeyens, Fred E. Moolekamp, David G. Monet, Marc Moniez, Serge Monkewitz, Christopher Montgomery, Christopher B. Morrison, Fritz Mueller, Gary P. Muller, Freddy Muñoz Arancibia, Douglas R. Neill, Scott P. Newbry, Jean-Yves Nief, Andrei Nomerotski, Martin Nordby, Paul O'Connor, John Oliver, Scot S. Olivier, Knut Olsen, William O'Mullane, Sandra Ortiz, Shawn Osier, Russell E. Owen, Reynald Pain, Paul E. Palecek, John K. Parejko, James B. Parsons, Nathan M. Pease, J. Matt Peterson, John R. Peterson, Donald L. Petravick, M. E. Libby Petrick, Cathy E. Petry, Francesco Pierfederici, Stephen Pietrowicz, Rob Pike, Philip A. Pinto, Raymond Plante, Stephen Plate, Joel P. Plutchak, Paul A. Price, Michael Prouza, Veljko Radeka, Jayadev Rajagopal, Andrew P. Rasmussen, Nicolas Regnault, Kevin A. Reil, David J. Reiss, Michael A. Reuter, Stephen T. Ridgway, Vincent J. Riot, Steve Ritz, Sean Robinson, William Roby, Aaron Roodman, Wayne Rosing, Cecille Roucelle, Matthew R. Rumore, Stefano Russo, Abhijit Saha, Benoit Sasselot, Terry L. Schalk, Pim Schellart, Rafe H. Schindler, Samuel Schmidt, Donald P. Schneider, Michael D.

Schneider, William Schoening, German Schumacher, Megan E. Schwamb, Jacques Sebag, Brian Selvy, Glenn H. Sembroski, Lynn G. Seppala, Andrew Serio, Eduardo Serrano, Richard A. Shaw, Ian Shipsey, Jonathan Sick, Nicole Silvestri, Colin T. Slater, J. Allyn Smith, R. Chris Smith, Shahram Sobhani, Christine Soldahl, Lisa Storrie-Lombardi, Edward Stover, Michael A. Strauss, Rachel A. Street, Christopher W. Stubbs, Ian S. Sullivan, Donald Sweeney, John D. Swinbank, Alexander Szalay, Peter Takacs, Stephen A. Tether, Jon J. Thaler, John Gregg Thayer, Sandrine Thomas, Adam J. Thornton, Vaikunth Thukral, Jeffrey Tice, David E. Trilling, Max Turri, Richard Van Berg, Daniel Vanden Berk, Kurt Vetter, Francoise Virieux, Tomislav Vucina, William Wahl, Lucianne Walkowicz, Brian Walsh, Christopher W. Walter, Daniel L. Wang, Shin-Yawn Wang, Michael Warner, Oliver Wiecha, Beth Willman, Scott E. Winters, David Wittman, Sidney C. Wolff, W. Michael Wood-Vasey, Xiuqin Wu, Bo Xin, Peter Yoachim, and Hu Zhan. LSST: From science drivers to reference design and anticipated data products. *The Astrophysical Journal*, 873(2):111, mar 2019.