

Galaxy Zoo DECaLS: Detailed visual morphology measurements from volunteers and deep learning for 314 000 galaxies

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ABSTRACT

We present Galaxy Zoo DECaLS: detailed visual morphological classifications for Dark Energy Camera Legacy Survey images of galaxies within the SDSS DR8 footprint. Deeper DECaLS images ($r = 23.6$ versus $r = 22.2$ from SDSS) reveal spiral arms, weak bars, and tidal features not previously visible in SDSS imaging. To best exploit the greater depth of DECaLS images, volunteers select from a new set of answers designed to improve our sensitivity to mergers and bars. Galaxy Zoo volunteers provide 7.5 million individual classifications over 314 000 galaxies. 140 000 galaxies receive at least 30 classifications, sufficient to accurately measure detailed morphology like bars, and the remainder receive approximately 5. All classifications are used to train an ensemble of Bayesian convolutional neural networks (a state-of-the-art deep learning method) to predict posteriors for the detailed morphology of all 314 000 galaxies. We use active learning to focus our volunteer effort on the galaxies which, if labelled, would be most informative for training our ensemble. When measured against confident volunteer classifications, the trained networks are approximately 99 per cent accurate on every question. Morphology is a fundamental feature of every galaxy; our human and machine classifications are an accurate and detailed resource for understanding how galaxies evolve.

Key words: methods: data analysis – galaxies: bar – galaxies: general – galaxies: interactions.

1 INTRODUCTION

Morphology is a key driver and tracer of galaxy evolution. For example, bars are thought to move gas inwards (Sakamoto et al. 1999) driving and/or shutting down star formation (Sheth et al. 2004; Jogee, Scoville & Kenney 2005), and bulges are linked to global quenching (Masters et al. 2011; Fang et al. 2013; Bluck et al. 2014) and inside-out quenching (Spindler et al. 2017; Lin et al. 2019). Morphology also traces other key drivers, such as the merger history of a galaxy. Mergers support galaxy assembly (Wang et al. 2011; Martin et al. 2018), though their relative contribution is an open question (Casteels et al. 2014), and may create tidal features,

bulges, and discs, allowing past mergers to be identified (Hopkins et al. 2010; Fontanot et al. 2011; Kaviraj 2014; Brooks & Christensen 2015).

Unpicking the complex interplay between morphology and galaxy evolution requires measurements of detailed morphology in large samples. While modern surveys reveal exquisite morphological detail, they image far more galaxies than scientists can visually classify. Galaxy Zoo solves this problem by asking members of the public to volunteer as ‘citizen scientists’ and provide classifications through a web interface. Galaxy Zoo has provided morphology measurements for surveys including SDSS (Lintott et al. 2008; Willett et al. 2013) and large *HST* programs (Simmons et al. 2017b; Willett et al. 2017).

Knowing the morphology of homogeneous samples of hundreds of thousands of galaxies supports science only possible at scale.

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The catalogues produced by the collective effort of Galaxy Zoo volunteers have been used as the foundation of a large number of studies of galaxy morphology (see Masters 2019 for a review), with the method's ability to provide estimates of confidence alongside classification especially valuable. Galaxy Zoo measures subtle effects in large populations (Masters et al. 2010; Willett et al. 2015; Hart et al. 2017); identifies unusual populations that challenge standard astrophysics (Simmons et al. 2013; Tojeiro et al. 2013; Kruk et al. 2017); and finds unexpected and interesting objects that provide unique data on broader galaxy evolution questions (Cardamone et al. 2009; Lintott et al. 2009; Keel et al. 2015).

Here, we present the first volunteer classifications of galaxy images collected by the Dark Energy Camera Legacy Survey (DECaLS; Dey et al. 2019). This work represents the first systematic engagement of volunteers with low-redshift images as deep as those provided by DECaLS, and thus represents a more reliable catalogue of detailed morphology than has hitherto been available. These detailed classifications include the presence and strength of bars and bulges, the count and winding of spiral arms, and the indications of recent or ongoing mergers. Our volunteer classifications were sourced over three separate Galaxy Zoo DECaLS (GZD) classification campaigns, GZD-1, GZD-2, and GZD-5, which classified galaxies first released in DECaLS Data Releases 1, 2, and 5, respectively. The key practical differences are that GZD-5 uses an improved decision tree aimed at better identification of mergers and weak bars, and includes galaxies with just 5 total votes as well as galaxies with 40 or more. Across all campaigns, we collect 7 496 325 responses from Galaxy Zoo volunteers, recording 30 or more classifications in at least one campaign for 139 919 galaxies and fewer (approximately 5 classifications) for an additional 173 870 galaxies, totalling 313 789 classified galaxies.

For the first time in a Galaxy Zoo data release, we also provide automated classifications made using Bayesian deep learning (Walmsley et al. 2020). By using our volunteer classifications to train a deep learning algorithm, we can make detailed classifications for all 313 789 galaxies in our target sample, providing morphology measurements faster than would be possible than relying on volunteers alone. Bayesian deep learning allows us to learn from uncertain volunteer responses and to estimate the uncertainty of our predictions. It also allows us to identify which galaxies, if labelled, would be most informative for training our classifier (active learning). We chose to partially focus our volunteers on such informative galaxies, requesting 40 classifications per informative galaxy and only 5 for the remainder. Our classifier predicts posteriors for how volunteers would have answered all decision tree questions,¹ with an accuracy comparable to asking 5 to 15 volunteers, depending on the question, and achieving approximately 99 per cent accuracy on every question for galaxies where the volunteers are confident (volunteer vote fractions below 0.2 or above 0.8).

In Section 2, we describe the observations used and the creation of RGB images suitable for classification. In Section 3, we give an overview of the volunteer classification process and detail the new decision trees used. In Section 4, we investigate the effects of improved imaging and improved decision trees, and we compare our results to other morphological measurements. Then, in Section 5, we describe the design and performance of our automated classifier – an ensemble of Bayesian convolutional neural networks. Finally, in Section 6, we provide guidance (and example code) for effective use of the classifications.

¹Excluding the final ‘Is there anything odd?’ question as it is multiple-choice.

2 IMAGING

2.1 Observations

Our galaxy images are created from data collected by the DECaLS survey (Dey et al. 2019). DECaLS uses the Dark Energy Camera (DECam; Flaugher et al. 2015) at the 4m Blanco telescope at Cerro Tololo Inter-American Observatory, near La Serena, Chile. DECam has a roughly hexagonal 3.2 deg² field of view with a pixel scale of 0.262 arcsec per pixel. The median point spread function full-width at half-maximum (FWHM) is 1''.29, 1''.18, and 1''.11 for g , r , and z , respectively.

The DECaLS survey contributes targeting images for the upcoming Dark Energy Spectroscopic Instrument (DESI). DECaLS is responsible for the DESI footprint in the Southern Galactic Cap (SGC) and the $\delta \leq 34$ region of the Northern Galactic Cap (NGC), totalling 10 480 deg².² 1130 deg² of the SGC DESI footprint are already being imaged by DECam through the Dark Energy Survey (DES; The Dark Energy Survey Collaboration 2005) so DECaLS does not repeat this part of the DESI footprint. DECaLS implements a 3-pass strategy to tile the sky. Each pass is slightly offset (approx. 0.1–0.6 deg). The choice of pass and exposure time for each observation is optimized in real-time based on the observing conditions recorded for the previous targets, as well as the interstellar dust reddening, sky position, and estimated observing conditions of possible next targets. This allows a near-uniform depth across the survey. In DECaLS DR1, DR2, and DR5, from which our images are drawn, the median 5σ point source depths for areas with 3 observations was approximately (AB) $g = 24.65$, $r = 23.61$, and $z = 22.84$.³ The DECaLS survey completed observations in 2019 March.

2.2 Selection

We identify galaxies in the DECaLS imaging using the NASA–Sloan Atlas v1.0.0 (NSA). As the NSA was derived from SDSS DR8 imaging (Aihara et al. 2011), this data release only includes galaxies that are within both the DECaLS and SDSS DR8 footprint. In effect, we are using deeper DECaLS imaging of the galaxies previously imaged in SDSS DR8. This ensures our morphological measurements have a wealth of ancillary information derived from SDSS and related surveys, and allows us to measure any shift in classifications versus Galaxy Zoo 2 using the subset of SDSS DR8 galaxies classified both in this work and in Galaxy Zoo 2 (Section 4). Fig. 1 shows the resulting GZ DECaLS sky coverage. NSA v1.0.0 was not published but the values of the columns used here are identical to those in NSA v1.0.1, released in SDSS DR13 (Albareti et al. 2017); only the column naming conventions are different.

Selecting galaxies with the NSA introduces two implicit cuts. First, the NSA primarily includes galaxies brighter than $m_r = 17.77$, the SDSS spectroscopic target selection limit. Galaxies fainter than $m_r = 17.77$ are included only if they are in deeper survey areas (e.g. Stripe82) or were measured using ‘spare’ fibres after all brighter galaxies in a given field were covered; we suggest researchers enforce their own magnitude cut according to their science case. Secondly, the NSA only covers redshifts of $z = 0.15$ or below. To these implicit cuts, we add an explicit cut requiring Petrosian radius (the NSA

²The remaining DESI footprint is being imaged by DECaLS’ companion surveys, MzLS and BASS (Dey et al. 2019).

³See <https://www.legacysurvey.org/dr5/description/> and related pages.

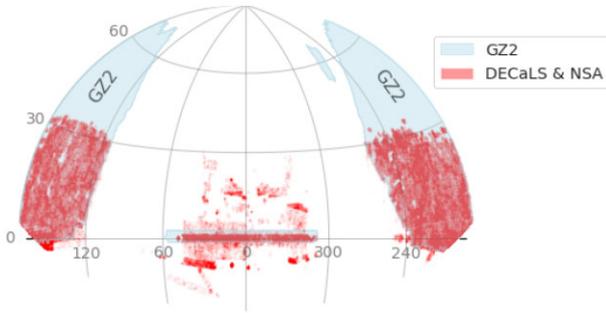


Figure 1. Sky coverage of GZ DECALS (equatorial coordinates), resulting from the imaging overlap of DECALS DR5 and SDSS DR8, shown in red. Darker areas indicate more galaxies. Sky coverage of Galaxy Zoo 2, which used images sourced from SDSS DR7, shown in light blue. The NSA includes galaxies imaged by SDSS DR8, including galaxies newly imaged at the Southern Galactic Cap (approx. 2500 deg²).

v1.0.0 PETROTHETA⁴ column) of at least 3 arcsec, to ensure the galaxy is sufficiently extended for meaningful classification.

For each galaxy, if the coordinates had been imaged in the g , r , and z bands, and the galaxy passed the selection cuts above, we acquired a combined FITS cutout of the grz bands from the DECALS cutout service (www.legacysurvey.org).

Galaxy Zoo presents volunteers with 424×424 pixel square galaxy images. GZD-1 and GZD-2 acquired 424×424 pixel square FITS cutouts directly from the cutout service. To ensure that galaxies typically fit well within a 424 pixel image, cutouts were downloaded with an interpolated pixel scale s of

$$s = \max(\min(0.04p_{50}, 0.02p_{90}), 0.1), \quad (1)$$

where p_{50} is the Petrosian 50 per cent-light radius and p_{90} is the Petrosian 90 per cent-light radius. Approximately 1 per cent of galaxies have incorrectly large radii reported in the NSA (typically as a result of foreground stars or other interloping sources) and this causes the field to be incorrectly large and hence the target galaxy to appear incorrectly small. To allow researchers to mitigate this issue, we flag images for which there are more source pixels away from the centre than near the centre; specifically, for which the mean distance of all likely source pixels⁵ exceeds 161 (approximately the expected value for all pixels). We find by eye that this simple procedure identifies the worst-affected galaxies. We report the mean source pixel distance and distance flags as `wrong_size_statistic` and `wrong_size_warning`, respectively.

For GZD-5, to avoid banding artefacts caused by the interpolation method of the DECALS cutout service, each FITS image was downloaded at the fixed native telescope resolution of 0.262 arcsec² per pixel,⁶ with enough pixels to cover the same area as 424 pixels at the interpolated pixel scale s . These individually sized FITS were then resized locally up to the interpolated pixel scale s by Lanczos interpolation (Lanczos 1938). Image processing is otherwise identical between campaigns. Galaxies with incomplete imaging, defined as more than 20 per cent missing pixels in any band, were

⁴Azimuthally averaged SDSS-style Petrosian radius, derived from the r band. See Albareti et al. (2017) and the NSA v1.0.1 data model.

⁵Arbitrarily defined as pixels with double the 20th percentile band-averaged value after the scaling in Section 2.3.

⁶Up to a maximum of 512 pixels per side. Highly extended galaxies were downloaded at reduced resolution such that the FITS had exactly 512 pixels per side.

discarded. For GZD-1/2, 92 960 of 101 252 galaxies had complete imaging (91.8 per cent). For GZD-5, 216 106 of 247 746 galaxies not in DECALS DR1/2 had complete imaging (87.2 per cent).⁷

2.3 RGB image construction

We convert the measured grz fluxes into RGB images following the methodology of Lupton et al. (2004). To use the grz bands as RGB colours, we multiply the flux values in each band by 125.0, 71.43, and 52.63, respectively. These numbers are chosen by eye⁸ such that typical subjects show an appropriate range of colour once mapped to RGB channels.

For background pixels with very low flux, and therefore high variance in the proportion of flux per band, naively colouring by the measured flux creates a speckled effect (Willett et al. 2017). As an extreme example, a pixel with 1 photon in the g band and no photons in r or z would be rendered entirely red. To remove these colourful speckles, we desaturate pixels with very low flux. We first estimate the total per-pixel photon count N assuming an exposure time of 90 seconds per band and a mean photon frequency of 600 nm. Poisson statistics imply the standard deviation on the total mean flux in that pixel is proportional to \sqrt{N} . For pixels with a standard deviation below 100, we scale the per-band deviation from the mean per-pixel flux by a factor of 1 per cent of the standard deviation. The effect is to reduce the saturation of low-flux pixels in proportion to the standard deviation of the total flux. Mathematically, we set

$$X'_{ijc} = \overline{X}_{ij} + \alpha(X_{ijc} - \overline{X}_{ij}) \quad \text{where } \alpha = \min(0.01\sqrt{\overline{X}_{ij}T/\lambda}, 1), \quad (2)$$

where X_{ijc} and X'_{ijc} are the flux at pixel ij in channel c before and after desaturation, \overline{X}_{ij} is the mean flux across bands at pixel ij , T is the mean exposure time (here, 90 s) and λ is the mean photon wavelength (here, 600 nm).

Pixel values were scaled by $\text{arcsinh}(x)$ to compensate for the high dynamic range typically found in galaxy flux, creating images which can show both bright cores and faint outer features. To remove the very brightest and darkest pixels, we linearly rescale the pixel values to lie on the $(-0.5, 300)$ interval and then clip the pixel values to 0 and 255, respectively. We use these final values to create an RGB image using `pillow` (Kemenade et al. 2020).

The images are available on Zenodo at <https://doi.org/10.5281/zenodo.4573248>. The code used to download the FITS cutouts and convert them to RGB images is available on GitHub for GZD-1, GZD-2, and GZD-5.

3 VOLUNTEER CLASSIFICATIONS

Volunteer classifications for GZ DECALS were collected during three campaigns. GZD-1 and GZD-2 classified all 99 109 galaxies passing the criteria above from DECALS DR1 and DR2, respectively. GZD-1 ran from 2015 September to 2016 February, and GZD-2 from 2016 April to 2017 February. GZD-5 classified 262 000 DECALS DR5-only galaxies passing the criteria above. GZD-5 ran from 2017 March to 2020 October. GZD-5 used more complex retirement criteria aimed at improving our automated classification (3.1) and an improved decision tree aimed at better identification of weak bars and minor mergers (4.2).

⁷Note that these numbers do not sum to the total number of galaxies classified across both campaigns because some galaxies are shared between campaigns.

⁸By Dustin Lang, who we gratefully acknowledge.

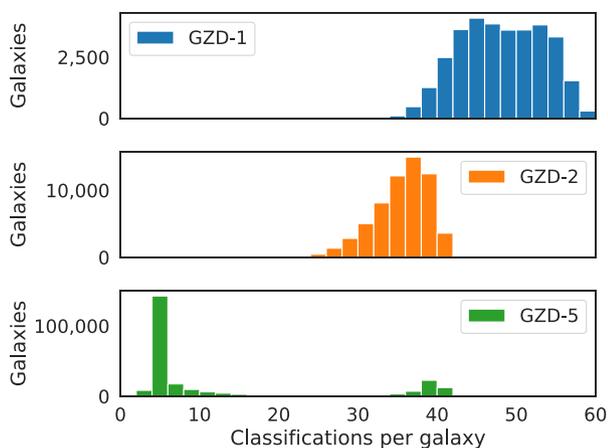


Figure 2. GZD-1, GZD-2, and GZD-5 classification counts, excluding implausible classifications (Section 4.3.1). GZD-1 has approximately 40–60 classifications, GZD-2 has approximately 40, and GZD-5 has either approximately 5 or approximately 30–40. 5.9 per cent of GZD-5 galaxies received more than 40 classifications due to mistaken duplicate uploads.

This iteration of the Galaxy Zoo project used the infrastructure made available by the Zooniverse platform; in particular, the open source Panoptes platform (The Zooniverse Team 2020). The platform allows for the rapid creation of citizen science projects, and presents participating volunteers with one of a subject set of images chosen either randomly, or through criteria described in Section 3.1.

3.1 Selecting total classifications

How many volunteer classifications should each galaxy receive? Ideally, all galaxies would receive enough classifications to be confident in the average response (i.e. the vote fraction) while still classifying all the target galaxies within a reasonable timeframe. However, the size of modern surveys make this increasingly impractical. Collecting 40 volunteer classifications for all 314 000 galaxies in this data release would have taken around eight years without further promotion efforts. The larger data sets of future surveys will only be more challenging. In anticipation of future classification demands, we have therefore implemented a variable retirement rate here (motivated and described further in Walmsley et al. 2020). Unlike previous data releases, GZ DECaLS galaxies each received different numbers of classifications (Fig. 2). Beginning part-way through GZD-5, we prioritize classifications for the galaxies expected to most improve our machine learning models, and rely more heavily on those models for classifying the remainder.

For GZD-1 and GZD-2, all galaxies received at least 40 classifications⁹ (as with previous data releases). GZD-1 galaxies have between 40 and 60 classifications, selected at random, while GZD-2 galaxies all have approximately 40. For GZD-5, galaxies classified until 2019 June also received approximately 40 classifications. From 2019 June, we introduced an active learning system. Using active learning, galaxies expected to be the most informative for training our deep learning model received 40 classifications, and the remaining galaxies received at least 5 classifications.

By ‘most informative’, we mean the galaxies which, if classified, would most improve the performance of our model. We describe our

method for estimating which galaxies would be most informative in full in Walmsley et al. (2020). Briefly, we use a convolutional neural network to make repeated predictions for the probability that k of N total volunteers select ‘Featured’ to the ‘Smooth or Featured’ question.¹⁰ For each prediction, we randomly permute the network with MC Dropout (Gal 2016), approximating (roughly) training many networks to make predictions on the same data set. It can be shown that, under some assumptions, the most informative galaxies will be the galaxies with confidently different predictions under each MC Dropout permutation; that is, where the permuted networks confidently disagree (Houlsby 2014). Formally, we acquire (label with volunteers) the galaxies with the highest estimated mutual information, given by:

$$I[k, w] = - \sum_{k=0}^N \langle \text{Bin}(k|f^w(x), N) \rangle \log \langle \text{Bin}(k|f^w(x), N) \rangle + \left\langle \sum_{k=0}^N \text{Bin}(k|f^w(x), N) \log [\text{Bin}(k|f^w(x), N)] \right\rangle, \quad (3)$$

where $f^w(x)$ is the output of the neural network trained to predict the typical volunteer response following Walmsley et al. (2020) and $\text{Bin}(k|f^w(x), N)$ is the probability for k of N volunteers to answer ‘Featured’ to ‘Smooth or Featured’ given that network-estimated typical response. Angled brackets indicate the expectation over the distribution of weights, approximated as the expectation over MC Dropout permutations. In short, the negative term gives the entropy of the volunteer vote distribution given the mean model predictions, and the positive term gives the mean entropy from the predictions of each permuted model. The difference between these terms measures the degree of confident disagreement between permuted models. See Walmsley et al. (2020) for more.

We used the same architecture and loss function as in Walmsley et al. (2020) while concurrently developing the more sophisticated classifier introduced in this Section. The initial training set was all GZD-5 galaxies fully classified ($N > 36$) by the time of activation. Each active learning cycle proceeded as follows. The model was retrained with all galaxies fully classified by the cycle start date. Next, unlabelled galaxies were ranked by mutual information (equation 3) and the most informative 1000 of a random 32 768¹¹ galaxies were uploaded. Once those galaxies were fully classified by volunteers (typically in 1–4 weeks) the cycle was repeated. 6939 total galaxies were uploaded in total.¹²

We chose to select from a subset of galaxies not yet classified for two reasons. The first was for computational efficiency: calculating the acquisition function requires making 5 predictions per galaxy. The second was that ad hoc experiments showed that galaxies with the very highest acquisition function values were often highly unusual and might be too unusual to learn from effectively. We also added a retirement rule to retire galaxies receiving 5 classifications of ‘artefact’, to help avoid volunteers being presented with these prioritized artefacts.

We emphasize that the number of classifications each galaxy received under active learning is not random. Fig. 3 shows how

⁹Note that because classifications from volunteers who respond ‘artefact’ at implausibly high rates are discounted, the total classifications in Fig. 2 and the published catalogue are slightly lower – see Section 4.3.1.

¹⁰‘Artifact’ answers are sufficiently rare that we chose to ignore votes for this answer when calculating which galaxies to label.

¹¹To allow for out-of-memory shuffling, binary-encoded galaxy images were stored in ‘shards’ of 4096 galaxies each. 32 768 corresponds to 8 such shards.

¹²Technical errors with duplicate uploads led to some active-learning-prioritized galaxies receiving more than 40 classifications; the median number of classifications is 44.

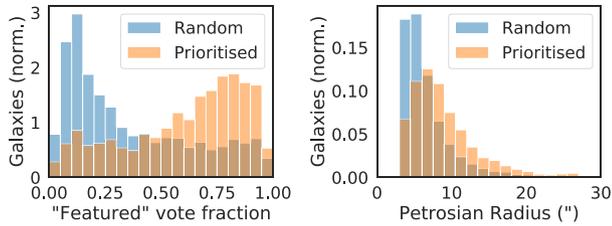


Figure 3. ‘Featured’ vote fraction and Petrosian radius (as measured by the NSA `PETROTHETA` column) for galaxies selected either at random (prior to enabling active learning) or prioritized as informative. Prioritized galaxies are dramatically more featured and slightly more extended than the previously classified random galaxies.

active-learning-prioritized galaxies are dramatically more featured and slightly more extended than the previously classified random galaxies, matching our intuition that small ‘smooth’ elliptical galaxies are easier to classify and hence less informative than extended ‘featured’ galaxies. For details on handling this and other selection effects, see Section 6.

3.2 Decision trees

The questions and answers we ask our volunteers define the measurements we can publish. It is therefore critical that the Galaxy Zoo decision tree matches the science goals of the research community.

The questions in a given Galaxy Zoo workflow are designed to be answerable even by a classifier with little or no astrophysical background. This motivates a focus primarily on the appearance of the galaxy, rather than incorporating physical interpretations which would require prior knowledge of galaxies. As an example, the initial question in all decision trees from Galaxy Zoo 2 onwards has asked the viewer to distinguish primarily between ‘smooth’ and ‘featured’ galaxies, rather than ‘elliptical’ and ‘disc’ galaxies. This distinction between descriptive and interpretive classification is not always perfectly enforced. For example, the ‘features’ response to the initial question is worded as ‘features or disc’, and a later question asks whether the galaxy is ‘merging or disturbed’, which requires some interpretation.¹³ To aid classifiers, all iterations of Galaxy Zoo have therefore included illustrative icons in the classification interface. Additional help is also available; in the current project, the interface includes a brief tutorial, a detailed field guide with multiple examples of each type of galaxy, and specific help text available for each individual classification task.

The largest workflow change between Galaxy Zoo versions was between the original Galaxy Zoo (GZ1) and Galaxy Zoo 2 (GZ2). GZ1 presented classifiers with a single task per galaxy, a choice between smooth/elliptical, multiple versions of featured/disc (including edge-on, face-on, and directionality of spiral structure), and merger. GZ2 re-classified the brightest quarter of the GZ1 sample in much greater detail, including a branched, multi-task decision tree. Subsequent changes to the decision tree for different versions of Galaxy Zoo have been mostly iterative in nature, driven in part by the data itself and in part by experience-based reflection which revealed minor adjustments that could help classifiers provide more accurate information. As an example of the former, a new branch was

¹³The step from visual description to interpretation may explain why a model trained by Fischer, Domínguez Sánchez & Bernardi (2019) on expert T-Type labels makes more confident predictions than volunteers on whether a subset of low-mass GZ2 galaxies show spiral structure; see Peterken et al. (2021).

added for GZ-Hubble and GZ-CANDELS to capture information on star-forming clumps in classifications of higher redshift galaxies. As an example of the latter, the final 2 tasks of GZ2 have been adjusted over multiple versions to facilitate reliable identification of rare features. Such adjustments have generally been minimized to avoid complicating comparisons with previous campaigns.

The decision tree used for GZD-1 and GZD-2 has three modifications versus the Galaxy Zoo 2 decision tree (Willett et al. 2013). The ‘Can’t Tell’ answer to ‘How many spiral arms are there?’ was removed, the number of answers to ‘How prominent is the central bulge?’ was reduced from four to three, and ‘Is the galaxy currently merging, or is there any sign of tidal debris?’ was added as a standalone question.

For GZD-5, we made three further changes. Several Galaxy Zoo studies (e.g. Masters et al. 2012; Skibba et al. 2012; Willett et al. 2013; Kruk et al. 2018) found that galaxies selected with $0.2 < p_{\text{bar}} < 0.5$ in GZ2 correspond to ‘weak bars’ when compared with expert classification such as those in Nair & Abraham (2010). Therefore, to increase the detection of bars, we changed the possible answers to the ‘Does this galaxy have a bar?’ question from ‘Yes’ or ‘No’ to ‘Strong’, ‘Weak’ or ‘No’. We define a strong bar as one that is clearly visible and extending across a large fraction of the size of the galaxy. A weak bar is smaller and fainter relative to the galaxy, and can appear more oval than the strong bar, while still being longer in one direction than the other. Our definition of strong versus weak bar is similar that of Nair & Abraham (2010), with the exception that they also have an ‘intermediate’ classification. We added examples of galaxies with ‘weak bars’ to the Field Guide and provided a new icon for this classification option, as shown in Fig. 4.

Secondly, to allow for more fine-grained measurements of bulge size, we increased the number of ‘How prominent is the central bulge?’ answers from three (‘No’, ‘Obvious’, ‘Dominant’) to five (‘No Bulge’, ‘Small’, ‘Moderate’, ‘Large’, ‘Dominant’). We also re-included the ‘Can’t Tell’ answer.

Thirdly, we modified the ‘Merging’ question from ‘Merging’, ‘Tidal’, ‘Both’, or ‘None’, to the more phenomenological ‘Merging’, ‘Major Disturbance’, ‘Minor Disturbance’, or ‘No’. Our goal was to present more direct answers to our volunteers and to better distinguish major and minor mergers, to support recent scientific interest in the role of major and minor mergers on mass assembly (López-Sanjuan et al. 2010; Kaviraj 2013), black hole accretion (Alexander & Hickox 2012; Simmons, Smethurst & Lintott 2017a), and morphology (Hopkins et al. 2009; Lotz et al. 2011; Lofthouse et al. 2017). We made this final ‘merger’ change two months after launching GZD-5; 6722 GZD-5 galaxies (2.7 per cent) were fully classified before that date and so do not have responses from volunteers to this question.

We also make several improvements to the illustrative icons shown for each answer. These icons are the most visible guide for volunteers as to what each answer means (complementing the tutorial, help text, field guide, and ‘Talk’ forum). Fig. 4 shows the GZD-5 decision tree with new icons as shown to volunteers. The decision tree used in GZD-1 and GZD-2 is shown in Fig. A1.

For the ‘Smooth or Featured?’ question, we changed the ‘Smooth’ icon to include three example galaxies at various ellipticities, and the ‘Featured’ icon to include an edge-on disc rather than a ring galaxy. For ‘Edge On?’, we replaced the previous tick icon with a new descriptive icon, and the previous cross icon with the ‘Featured’ icon above. We also modified the text to no longer specify ‘exactly’ edge on, and renamed the answers from ‘Yes’ and ‘No’ to ‘Yes - Edge On Disc’ and ‘No - Something Else’. For ‘Bulge?’, we created new icons to match the change from four to five answers. For ‘Bar’, we replaced the previous tick and cross icons with new descriptive

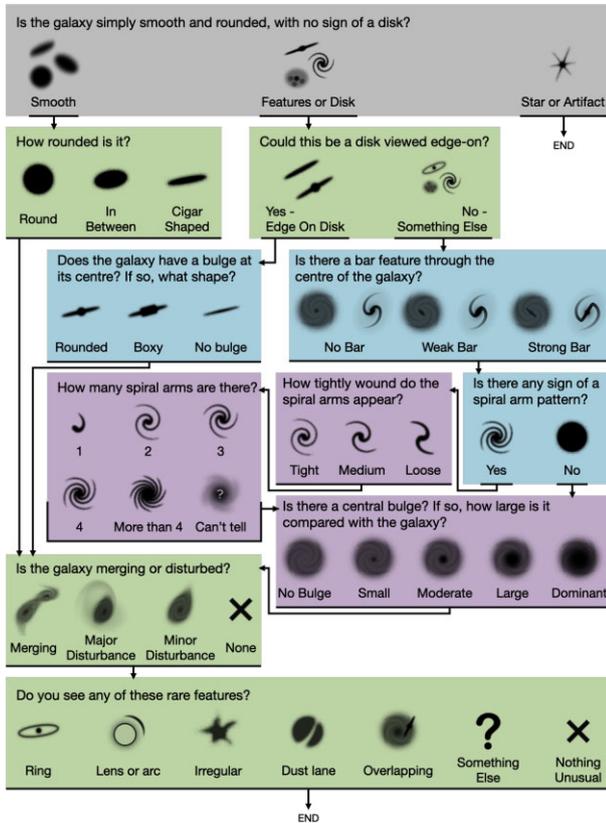


Figure 4. Classification decision tree for GZD-5, with new icons as shown to volunteers. Questions shaded with the same colours are at the same level of branching in the tree; grey have zero-dependent questions, green one, blue two, and purple three.

icons for ‘Strong Bar’, ‘Weak Bar’, and ‘No Bar’. For ‘Merger?’, we added new descriptive icons to match the updated answers.

Changes to the decision tree complicate comparisons other Galaxy Zoo projects. As we show in the following sections, the available answers will affect the sensitivity of volunteers to certain morphological features, and so morphology measurements made with different decision trees may not be directly comparable. This difficulty in comparison has historically required us to be conservative in our changes to the decision tree. However, the advent of effective automated classifications allows us to retrospectively make classifications using any preferred decision tree. Specifically, in this work, we train our automated classifier to predict what volunteers would have said using the GZD-5 decision tree, for galaxies which were originally classified by volunteers using the GZD-1/2 decision tree (Section 5.1).

4 VOLUNTEER ANALYSIS

4.1 Improved feature detection from DECaLS imagery

The images used in GZ DECaLS are deeper and higher resolution than were available for GZ2. The GZ2 primary sample (Willett et al. 2013) uses images from SDSS DR7 (Abazajian et al. 2009), which are 95 per cent complete to $r = 22.2$ with a median seeing of $1''.4$ and a plate scale of $0''.396$ per pixel (York et al. 2000). In contrast, GZ DECaLS uses images from DECaLS DR2 to DR5, which have a median 5σ point source depth of $r = 23.6$, a seeing better than $1''.3$

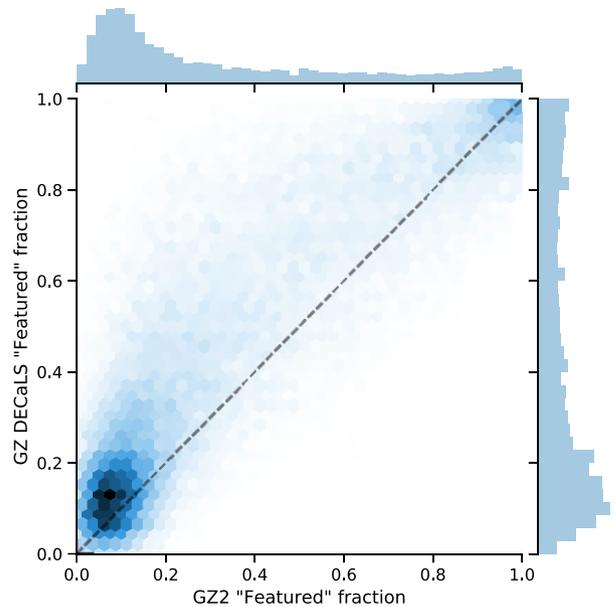


Figure 5. Comparison of ‘Featured’ fraction for galaxies classified in both GZ2 and GZ DECaLS. Ambiguous galaxies are consistently reported as more featured in GZ DECaLS, which we attribute to the significantly improved imaging depth of DECaLS.

for at least one observation, and a plate scale of $0''.262$ per pixel (Dey et al. 2019),¹⁴

We expect the improved imaging to reveal morphology not previously visible, particularly for features which are faint (e.g. tidal features, low surface brightness spiral arms) or intricate (e.g. weak bars, flocculent spiral arms). Our changes to the decision tree (Section 3.2) were partly made to better exploit this improved imaging.

To investigate the consequences of improved imaging, we compare galaxies classified in both GZ2 and GZ DECaLS. Galaxies will typically be classified by both projects if they are inside both the SDSS DR7 Legacy catalogue (i.e. the source GZ2 catalogue) and DECaLS DR5 footprints (broadly, North Galactic Cap galaxies with $-35 < \delta < 0$) and match the selection criteria of each project (see Willett et al. 2013 and Section 2.2). GZ2’s $r < 17.0$ cut, with no corresponding GZ DECaLS magnitude cut, means that the odds of any given GZ2 galaxy being in GZ DECaLS is close to random (for an isotropic sky) but only the brighter half of suitably located GZ DECaLS galaxies are in GZ2. To exclude the effect of modifying the decision tree in GZD-5 (addressed separately in Section 4.2), we use only GZ DECaLS classifications from GZD-1 and GZD-2. 33 124 galaxies were classified in both GZ2 and GZD-1 or GZD-2.

We find that volunteers successfully recognize newly visible morphology features. Fig. 5 compares the distribution of vote fractions to ‘Is this galaxy smooth or featured?’ for GZ2 and GZ DECaLS. Ambiguous galaxies, with ‘featured’ fractions (before debiasing) between approx. 0.25 and 0.75, are consistently reported as more featured (median absolute increase of 0.13, median percentage increase of 22 per cent) with the deeper GZ DECaLS images.

The shift towards featured galaxies is an accurate response to the new images, rather than systematics from (for example) a changing population of volunteers. Fig. 6 compares the GZ2 and GZ DECaLS

¹⁴See also <http://www.legacysurvey.org/dr5/description/>.

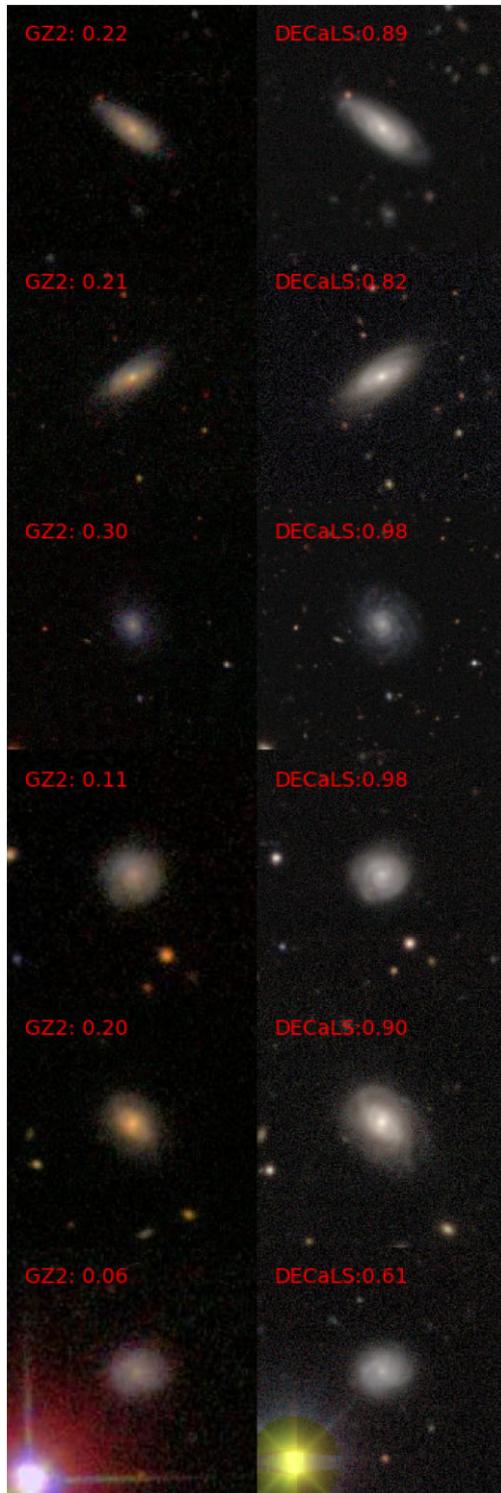


Figure 6. GZ2 and GZ DECaLS images for 6 galaxies drawn randomly from the 1000 galaxies classified in both projects with the largest increase in ‘featured’ vote fraction (reported fractions shown in red). The increased fraction accurately reflects the increased visibility of detailed morphology from improved imaging.

images of a random sample of galaxies drawn from the 1000 cross-classified galaxies with the largest increase in ‘featured’ fraction. In all of these galaxies (and for a clear majority of galaxies in similar samples), volunteers are correctly recognizing newly visible detailed features.

We observe a similar pattern in the vote fractions of spiral arms and bars for featured galaxies. For galaxies consistently considered featured (i.e. where both projects reported a ‘featured’ vote fraction of at least 0.5), the median vote fraction for spiral arms increased from 0.84 to 0.9, and for bars from 0.21 to 0.24. This suggests that even for galaxies where some details were already visible (and hence were considered featured), improved imaging makes our volunteers more likely to identify specific features.

We argue the improved depth of DECaLS ($r = 23.6$ versus $r = 22.2$ for SDSS) is revealing low surface brightness features that were previously ambiguous. There may also be contributions from the modified image processing approach and from the shift between using *gri* bands (SDSS) to *grz* bands (DECaLS), which might make older stars more prominent.

Comparing classifications made using the same possible answers on the same galaxies shows how improved DECaLS imaging leads to ambiguous galaxies being correctly reported as more featured, and to spiral arms and bars being reported with more confidence. However, volunteers are also sensitive to which questions are asked and how those questions are asked. We measure the impact of our changes to the decision tree ‘Bar’ question for GZD-5 in the next section.

4.2 Improved weak bar detection from GZD-5 decision tree

To measure the effect of the new decision tree on bar sensitivity, we compare the classifications made using each tree against expert classifications. Nair & Abraham (2010; hereafter **NA10**) classified all 14 034 SDSS DR4 galaxies at $0.01 < z < 0.05$ with $g < 16$. Of those, 1497 were imaged by DECaLS DR1/2 and classified by volunteers during GZD-1/2. We re-classified these galaxies during GZD-5 to measure the effect of the new bar answers, as compared to the expert classifications of **NA10**. Note that because **NA10** used shallower SDSS images, **NA10**’s classifications are best used as positive evidence; while **NA10** finding a bar in SDSS images implies a visible bar in DECaLS images, **NA10** not finding a bar may not always exclude a visible bar in DECaLS. To exclude smooth galaxies, which are unbarred by definition in our schema, we require $f_{\text{featured}} > 0.25$ (as measured by GZD-5), selecting a featured sample of 807 galaxies classified by **NA10**, GZD-1/2, and GZD-5.

Fig. 7 compares volunteer classifications for expert-labelled calibration galaxies made using each tree. We find that barred and unbarred galaxies are significantly better separated with the Strong/Weak/None answers than with Yes/No answers. Of 220 Nair-identified bars (of any type), 184 (84 per cent) receive a majority vote for being barred by volunteers using the new tree, up from 120 (55 per cent) with the previous tree.

NA10 classified barred galaxies into five subtypes: Strong, Intermediate, Weak, Nuclear, Ansa, and Peanut (plus None, implicitly). We can use the first three subtypes as a measurement of expert-classified bar strength, and therefore evaluate how our volunteers respond to bars of different strengths. Following the approach to defining summary metrics of Masters et al. (2019), we summarize the bar vote fractions into a single volunteer estimate of bar strength, $B_{\text{vol}} = f_{\text{strong}} + 0.5f_{\text{weak}}$, and compare the distribution of B for each expert-classified bar strength (Fig. 8). We find that the volunteer bar strength estimates increase smoothly with expert-classified bar strength, though individual galaxies vary substantially. This suggests

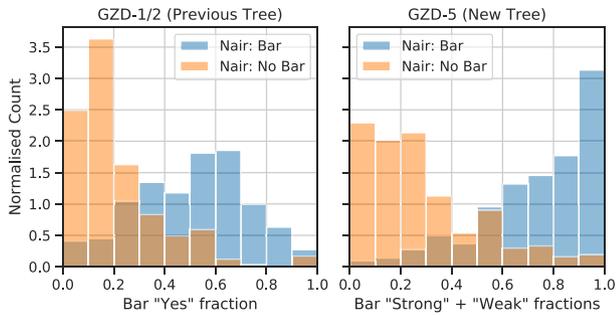


Figure 7. Left-hand panel: Distribution of fraction of GZD-1/2 volunteers answering ‘Yes’ (not ‘No’) to ‘Does this galaxy have a bar?’, split by expert classification from NA10 of barred (blue) or unbarred (orange). Right-hand panel: as left, but for GZD-5 volunteers answering ‘Strong’ or ‘Weak’ (not ‘No’). Volunteers are substantially better at identifying barred galaxies using the GZD-5 three-answer question.

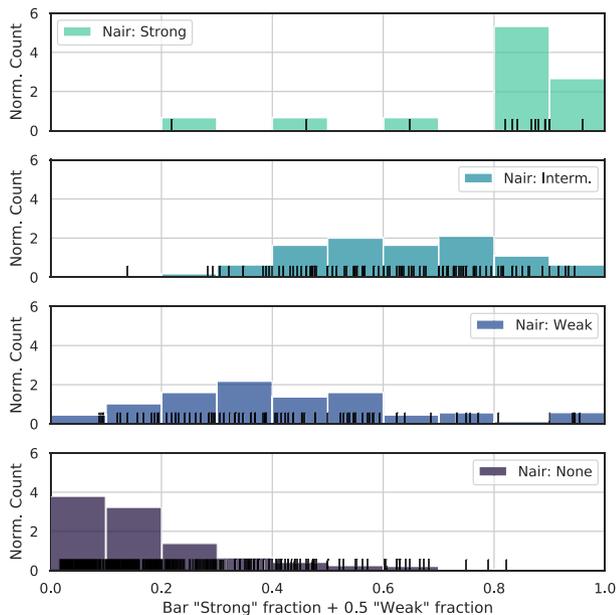


Figure 8. Distributions of volunteer bar strength estimates, $B_{\text{vol}} = f_{\text{strong}} + 0.5f_{\text{weak}}$, split by expert-classified (NA10) bar strength. Individual galaxies are shown with rug plots (15 Strong, 110 Intermediate, 87 Weak, and 377 None). Volunteer bar strength estimates increase smoothly with expert-classified bar strength, though individual galaxies vary substantially.

that typical bar strength in galaxy samples can be successfully inferred from volunteer votes.

The addition of the ‘weak bar’ answer in GZD-5 significantly improves sensitivity to bars compared with previous versions of the decision tree. Additionally, volunteer votes across the three answers may be used to infer bar strength. We hope that the detailed bar classifications in our catalogue will help researchers better understand the properties of strong and weak bars and their influence on host galaxies.

4.3 Classification modifications

Galaxy Zoo data releases have previously included two post-hoc modifications to the volunteer classifications; volunteer weighting, to reduce the influence of strongly atypical volunteers, and redshift debiasing, to estimate the vote fractions a galaxy might have received

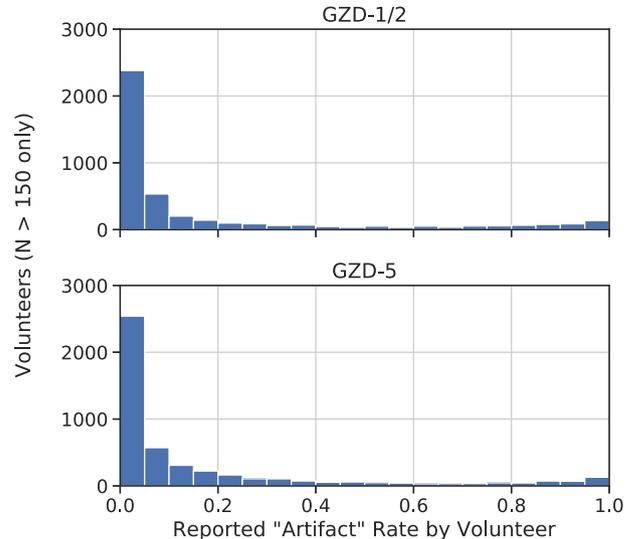


Figure 9. Distribution of reported ‘artifact’ rates by volunteer (i.e. how often each volunteer answered ‘artifact’ over all the galaxies they classified). The vast majority report artifact rates consistent with those of the authors (below 0.1), but a very small subset report implausibly high artifact rates (> 0.5) and consequently have their classifications discarded. Only volunteers with at least 150 classifications are shown; the distribution for volunteers with fewer classifications is not bimodal.

had it been observed at a specific redshift. We describe each modification below.

4.3.1 Volunteer weighting

Volunteer weighting, as introduced in Galaxy Zoo 2 (Willett et al. 2013), assigns each volunteer an aggregation weight of (initially) one, and iteratively reduces that weight for volunteers who typically disagree with the consensus. This method affects relatively few volunteers and therefore causes only a small shift in vote fractions - in Galaxy Zoo 2, for example, approximately 95 per cent of volunteers had a weighting of one (i.e. unaffected), 94.8 per cent of galaxies had a change in vote fraction of no more than 0.1 for any question, and the mean change in vote fraction across all questions and galaxies was 0.0032.

The most significant change in final vote fractions is caused by downweighting rare (approx. 1 per cent) volunteers who repeatedly disagree with consensus by answering ‘artifact’ at implausibly high rates (including 100 per cent) for many galaxies. Answering artifact ends the classification and shows the next galaxy, and so we hypothesize that these rare volunteers are primarily interested in seeing many galaxies rather than contributing meaningful classifications. There are very few such volunteers, but because answering artifact allows classifications to be submitted very quickly, they have an outsize effect on the aggregate vote fractions.

Fig. 9 shows the distribution of reported artifact rates for volunteers with at least 150 total classifications. We expect the true fraction of artifacts to be less than 0.1, and the vast majority of volunteers report artifact rates consistent with this. However, the distribution is bimodal, with a small second peak around 1.0 (i.e. volunteers reporting every galaxy as an artifact). To remove the implausible mode, we discard the classifications of volunteers with at least 150 total classifications and reported artifact rates greater than 0.5. In GZD-1/2, 1.1 per cent (643) of volunteers are excluded, discarding 11 per cent (483 081) of classifications. In GZD-5, 0.03 per cent

(543) volunteers are excluded, discarding 5.3 per cent (249 592) of classifications.

We investigated the possibility of other groups of atypical volunteers giving similar answers across questions by analysing the per-user vote fractions with either a 2D visualization using UMAP (McInnes, Healy & Melville 2018) or with clustering using HDBSCAN (McInnes, Healy & Astels 2017). We find no strong evidence that such clusters exist.

4.3.2 Redshift debiasing

Galaxies at higher redshifts appear fainter and smaller on the sky, making it harder to detect detailed morphological features than if the galaxy were closer. This creates a bias in visual classifications (whether human or automated) where galaxies of the same intrinsic morphology are less likely to be classified as having detailed features as redshift increases (Bamford et al. 2009). Redshift debiasing is an attempt to mitigate this bias by estimating how a galaxy would appear if it were at a fixed low redshift (here, $z = 0.02$).

We use the method described in Hart et al. (2016) to remove the redshift bias, which we briefly summarize here and refer the reader to their Section 3 for full details. We assume the morphological properties of galaxies (as probed by our decision tree) over the redshift window covered by Galaxy Zoo DECaLS ($0.02 < z < 0.15$, approximately 1.5 Gyr) do not evolve significantly for galaxies of similar intrinsic brightness and physical size, and so, for a luminosity-limited sample, any change we observe to the vote fraction distribution as a function of redshift is purely a consequence of imaging. If so, we can estimate the vote fractions which would be observed if each galaxy were at low redshift by modifying the vote fractions of higher redshift galaxies such that they have the same overall distribution as their low-redshift counterparts in brightness and size.

We base the debiasing on a luminosity-limited sample, selected between $0.02 < z < 0.15$ and $-21.5 > M_r > -23$. We consider the galaxies with at least 30 votes for the first question (‘Smooth or Featured’) after volunteer weighting (above), for a total of 87 617 galaxies in GZD-1/2 and 58 916 galaxies in GZD-5. For each question, separately, we define a subset of galaxies to which we apply the debiasing procedure.

Each subset is defined using a cut of $f > 0.5$ for the chain of preceding questions (for example, for the bar question, we require $f_{\text{feat}} \times f_{\text{not edge-on}} > 0.5$). A further cut of $N > 5$ (where N is the number of classifications) is also imposed to ensure that each galaxy has been classified by a significant number of people. We bin the subset of galaxies by M_r , $\log(R_{50})$ and z for each answer in turn. We use the `voronoi_2d_binning` package from Cappellari & Copin (2003) to ensure the bins will have an approximately equal number of galaxies (with a minimum of 50). We then match vote fraction distributions on a bin-by-bin basis, such that the cumulative distribution of vote fractions at each redshift is shifted to be similar to that of the lowest redshift sample ($0.02 < z < 0.03$). This method aims to keep the fraction of galaxies above a given threshold constant with redshift.

The effect of redshift bias and redshift debiasing question is shown in Fig. 10. To illustrate, consider the ‘Smooth or Featured’ question (top left-hand panel). In a luminosity-limited sample, there should be the same fraction of galaxies with features (selected with $f_{\text{feat}} > 0.5$) at all redshifts. However, we observe that the fraction of ‘featured’ galaxies decreases, and the fraction of ‘smooth’ galaxies increases (solid lines). We attribute this to redshift bias; some galaxies that

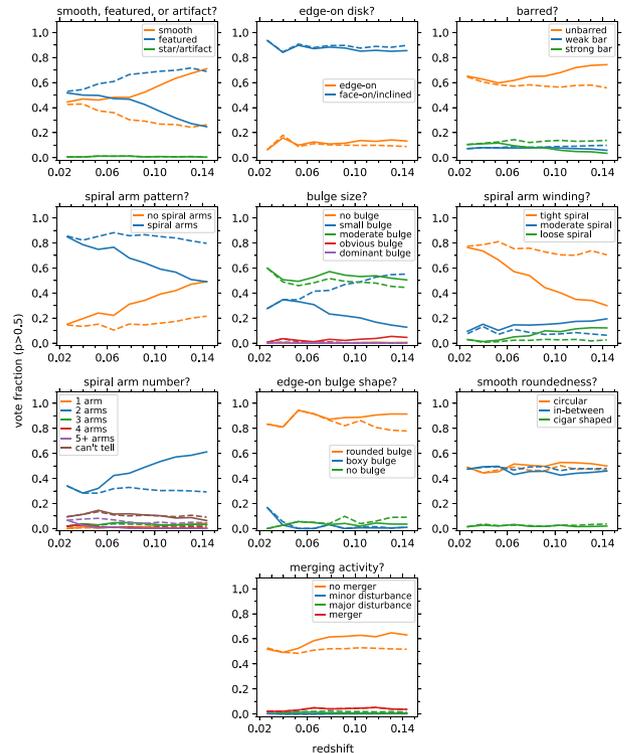


Figure 10. Number of GZD-5 galaxies with $f > 0.5$ for each of the questions debiased using the method described in Section 4.3.2. The solid lines indicate the original vote fractions and the dashed lines indicate the debiased vote fractions. The total sample here is composed of galaxies in the luminosity-limited sample with $f > 0.5$, 58 916 galaxies. For most questions and answers, debiasing successfully flattens the redshift trends. For ‘Smooth or Featured’ and ‘Bulge Prominence’, redshift debiasing overcorrects.

would be considered featured if imaged at low redshift appear as ‘fuzzy blobs’ at high redshift and are instead classified as smooth. After applying redshift debiasing, the debiased fractions (dashed lines) change more gradually with redshift. For most questions and answers, the redshift trend is successfully flattened (recall that for every size and luminosity bin, we enforce no change in the vote fraction distribution with redshift). For ‘Smooth or Featured’ and ‘Bulge Prominence’, the debiasing procedure overcorrects and hence reverses the redshift trend.

For statistical studies, it is important to test for the presence of a classification bias with redshift and correct it where necessary. Such a correction has proven essential in studies of the morphology density relation (Bamford et al. 2009) and when characterizing populations with different spiral arm properties (Hart et al. 2016). However, while debiasing can be extremely useful, there are caveats to its usage. It is sometimes helpful to think of the original classifications as a lower limit to the probability of features of a given type existing in a galaxy. Debiasing predicts what the classifications would be if the same galaxy were imaged at lower redshift, which is typically more featured than the original classifications. There is substantial uncertainty in this prediction, however, and this is currently not captured by the debiased vote fractions, which are reported without error bars.

In some investigations, it may be helpful to consider that the true classification for a given galaxy is likely to be in between the original classification and the debiased classification. At the same time, the debiased classifications are not strictly upper limits. They are based on the lowest redshift classifications within the data set itself,

which themselves are at a non-zero redshift, and so there are likely differences in the debiased classifications and the ‘true’ debiased classification that would be assigned if we could image the galaxy at arbitrarily low redshift. As these corrections are applied uniformly, however, they are useful when considering overall populations of galaxies within a given data set and over the redshift ranges where the correction is relevant. In particular, when comparing different morphological types, some of the systematic errors in the debiasing may cancel out. Uncertainties in the debiasing will also decrease as the sample size increases.

For these reasons, we strongly suggest that users of the debiased classifications only use them to consider populations of galaxies rather than individual or small samples, and to consider that there may still be some residual trends and uncertainties that are hard to model with current methods.

5 AUTOMATED CLASSIFICATIONS

Combining citizen science with automated classification allows us to do better science than with either alone. The clearest benefit is that automated classification scales well with sample size. For GZ DECaLS, classifying all 311 488 suitable galaxies using volunteers alone is infeasible; collecting 40 classifications per galaxy, the standard from previous Galaxy Zoo projects, would take around eight years without further promotion efforts – by which time we expect new surveys to start. Automated classification also evolves – as the quality of our models improves, so too will the quality of our classifications. And automated classification is replicable from scratch without requiring a crowd – other researchers may run our open-source code and recover our classifications (within stochasticity), or create equivalent classifications for newly imaged galaxies.

Finally, and of particular relevance to researchers using this data release, automated classification allows us to retroactively update the decision tree. Because our classifier learns to make predictions from GZD-5 classifications, using the improved tree with better detection of mergers and weak bars, we can then predict what our volunteers would have said for the GZD-1 and GZD-2 galaxies had we been using the improved tree at that time.

Our specific automated classification approach offers several qualitative benefits over previous work. First, through careful consideration of uncertainty, we can both learn from uncertain volunteer responses and predict posteriors (rather than point estimates) for new galaxies. Secondly, by predicting the answers to every question with a single model (similarly to Dieleman, Willett & Dambre 2015, and unlike more recent work e.g. Sánchez et al. 2018; Khan et al. 2019; Walmsley et al. 2020), we improve performance by sharing representations between tasks (Caruana 1997) – intuitively, knowing how to recognize spiral arms can also help you count them. Learning from every galaxy to predict every answer uses our valuable volunteer effort as efficiently as possible. This is particularly effective because we aim to predict detailed morphology, and hence learn to create a detailed representation of each galaxy.

5.1 Bayesian deep learning classifier

We require a model which can:

- (i) Learn efficiently from volunteer responses of varying (i.e. heteroskedastic) uncertainty.
- (ii) Predict posteriors for those responses on new galaxies, for every question.

In previous work (Walmsley et al. 2020), we modelled volunteer responses as being binomially distributed and trained our model to make maximum-likelihood estimates using the loss function

$$\mathcal{L} = k \log f^w(x) + (N - k) \log(1 - f^w(x)), \quad (4)$$

where for some target question, k is the number of responses (successes) of some target answer, N is the total number of responses (trials) to all answers, and $f^w(x) = \hat{\rho}$ is the predicted probability of a volunteer giving that answer.

This Binomial assumption, while broadly successful, broke down for galaxies with vote fractions $\frac{k}{N}$ close to 0 or 1, where the Binomial likelihood is extremely sensitive to $f^w(x)$, and for galaxies where the question asked was not appropriate (e.g. predict if a featureless galaxy has a bar). Instead, in this work, the model predicts a distribution $p(\rho|f^w(x))$ and ρ is then drawn from that distribution.

For binary questions, one could parametrize $p(\rho|f^w(x))$ with the Beta distribution (being flexible and defined on the unit interval), and predict the Beta distribution parameters $f^w(x) = (\hat{\alpha}, \hat{\beta})$ by minimizing

$$\mathcal{L} = \int \text{Bin}(k|\rho, N) \text{Beta}(\rho|\alpha, \beta) d\alpha d\beta, \quad (5)$$

where the Binomial and Beta distributions are conjugate and hence this integral can be evaluated analytically.

In practice, we would like to predict the responses to questions with more than two answers, and hence we replace each distribution with its multivariate counterpart; Beta($\rho|\alpha, \beta$) with Dirichlet($\vec{\rho}|\vec{\alpha}$), and Binomial($k|\rho, N$) with Multinomial($k|\vec{\rho}, N$).

$$\mathcal{L}_q = \int \text{Multi}(k|\rho, N) \text{Dirichlet}(\rho|\alpha) d\alpha, \quad (6)$$

where \vec{k} , $\vec{\rho}$, and $\vec{\alpha}$ are now all vectors with one element per answer.

The Dirichlet-Multinomial distribution is much more flexible than the Binomial, allowing our model to express uncertainty through wider posteriors and confidence through narrower posteriors. We believe this is a novel approach.

For the base architecture, we use the EfficientNet B0 model (Tan & Le 2019). The EfficientNet family of models includes several architectural advances over the standard convolutional neural network architectures commonly used within astrophysics (e.g. Dieleman et al. 2015; Huertas-Company et al. 2015; Khan et al. 2019; Cheng et al. 2020; Ferreira et al. 2020), including auto-ML-derived structure (He, Zhao & Chu 2019; Tan et al. 2019), depthwise convolutions (Howard et al. 2017), bottleneck layers (Iandola et al. 2017), and squeeze-and-excitation optimization (Hu, Shen & Sun 2018). The EfficientNet B0 model was identified using multi-objective neural architecture search (Tan et al. 2019), optimizing for both accuracy and FLOPS (i.e. computational cost of prediction). This balancing of accuracy and FLOPS is particularly useful for astrophysics researchers with limited access to GPU resources, leading to a model capable of making reliable predictions on hundreds of millions of galaxies. In short, the architecture is similar to traditional convolutional neural networks, being composed of a series of convolutional blocks of decreasing resolution and increasing channels. Each convolutional block uses mobile inverted bottleneck convolutions following MobileNetV2 (Sandler et al. 2018), which combine computationally efficient depthwise convolutions with residual connections between bottlenecks (as opposed to residual connections between blocks with many channels, as in e.g. ResNet; He et al. 2016). EfficientNet B0 has 5.3 million parameters.

We modify the final EfficientNet B0 layer output units to give predictions smoothly between 1 and 100 (using softmax activation),

which is appropriate for Dirichlet parameters $\vec{\alpha}$. $\vec{\alpha}$ elements below 1 can lead to bimodal ‘horseshoe’ posteriors, and $\vec{\alpha}$ elements above approximately 100 can lead to extremely confident predictions in extreme ρ , both of which are implausible for galaxy morphology posteriors. These constraints may cause the most extreme galaxies to have predicted vote fractions which are slightly less extreme than volunteers would record, but we do not anticipate this to affect practical use; whether a galaxy is extremely likely to have a bar or merely highly likely is rarely of scientific consequence.

We would like our single model to predict the answer to every question in the Galaxy Zoo tree. To do this, our architecture uses one output unit per answer (i.e. for 13 questions with a total of 20 answers, we use 20 output units). We calculate the (negative log) likelihood per question (equation 6), and then, treating the errors in the model’s answers to each question as independent events, calculate the total loss as

$$\log \mathcal{L} = \sum_q \mathcal{L}_q(\mathbf{k}_q, N_q, \vec{f}_q^w), \quad (7)$$

where for question q , N_q is the total answers, \vec{k}_q is the observed votes for each answer, and \vec{f}_q^w is the values of the output units corresponding to those answers (which we interpret as the Dirichlet $\vec{\alpha}$ parameters in equation 6).

We train our model using the GZD-5 volunteer classifications. Because the training set includes both active-learning-selected galaxies receiving at least 40 classifications and the remaining GZD-5 galaxies with around 5 classifications, it is crucial that the model is able to learn efficiently from labels of varying uncertainty. Unlike Walmsley et al. (2020), which trained one model per question and needed to filter galaxies where that question asked may not be appropriate, we can predict answers to all questions and learn from all labelled galaxies.

We train or evaluate our models using the 249 581 (98.5 per cent) GZD-5 galaxies with at least three volunteer classifications. Learning from galaxies with even fewer (one or two) classifications should be possible in principle, but we do not attempt it here as we do not expect galaxies with so few classifications to be significantly informative. The Dirichlet concentrations (distribution parameters) used to calculate our metrics are predicted by three identically trained models, each making 5 forward passes with random dropout configurations and augmentations. We ensemble all 15 forward passes by simply taking the mean posterior given the total votes recorded, which may be interpreted as the posterior of an equally-weighted mixture of Dirichlet-Multinomial distributions. This mean posterior can then be used to calculate credible intervals (error bars) and in standard statistical analyses. We develop our approach using a conventional 80/20 train-test split, and make a new split before calculating the final metrics reported here.

For the published automated classifications, where we aim simply to make the best predictions possible rather than to test performance, we train on all 249 581 galaxies with at least 3 votes (98.5 per cent). We also train five rather than three models to maximize performance. Training each model on an NVIDIA V100 GPU takes around 24 h. We then make predictions (using the updated GZD-5 schema) on all 313 789 galaxies in all campaigns. Each prediction (forward pass) takes approx. 6 ms, equating to approx. 160 ms for each published posterior.

Starting from the galaxy images shown to volunteers (Section 2.3), we take an average over channels to remove colour information and avoid biasing our morphology predictions (Walmsley et al. 2020),

then resize and save the images as $300 \times 300 \times 1$ matrices. We then apply random augmentations when loading each image into memory, creating a unique randomly modified image to be used as input to the network. We first apply random horizontal and vertical flips, followed by an aliased rotation by a random angle in the range $(0, \pi)$, with missing pixels being filled by reflection on the boundaries. Finally, we crop the image about a random centroid to 224×224 pixels, effectively zooming in slightly towards a random off-centre point. We also apply these augmentations at test time to marginalize our posteriors over any unlearned variance. We train using the Adam (Kingma & Ba 2015) optimizer and a batch size of 128. We end training once the model loss fails to improve for 10 consecutive epochs.

Code for our deep learning classifier, including extensive documentation and several worked examples, is available at <https://github.com/mwalmsley/zoobot>.

5.2 Results

Our model successfully predicts posteriors for volunteer votes to each question. We show example posteriors for a question with two answers, ‘Does this galaxy have spiral arms’ (Yes/No), in Fig. 11, and a question with three answers, ‘Does this galaxy have a bar’ (Strong/Weak/None), in Fig. 12. In Appendix A, we provide a gallery of the galaxies with the highest expected vote fractions for a selection of answers, to visually demonstrate the quality of the most confident machine classifications.

To aid intuition for the typical performance, we reduce both the vote fraction labels and the posteriors down to discrete classifications by rounding the vote fractions and mean posteriors to 0 or 1, and calculate classification metrics (Table 1) and confusion matrices (Fig. 13). Here and throughout this section, we calculate performance on the 11 346 galaxies in the (random) test set with at least 34¹⁵ classifications (such that the typical volunteer answer is well-measured). To remove galaxies for which the question is not relevant, we only count galaxies where at least half the volunteers were asked that question. We report two sets of classification metrics; metrics for all (relevant) galaxies, and only for galaxies where the volunteers are confident (defined as having a vote fraction for one answer above 0.8, following Domínguez Sánchez et al. 2019).

The performance on confident galaxies is useful to measure because such galaxies have a clear correct label. For such galaxies, performance is near-perfect; we achieve better than 99 per cent accuracy for most questions, with the lowest accuracy (for spiral arm count) being 98.6 per cent. The confusion matrices reflect this, showing little notable confusion for any question.

Reported performance on all galaxies will be lower than on confident galaxies as the correct labels are uncertain. Our measured vote fractions are approximations of the theoretical ‘true’ vote fractions (as we cannot ask infinitely many volunteers), and many galaxies are genuinely ambiguous and do not have a meaningful ‘correct’ answer. No classifier should achieve perfect accuracy on galaxies where the volunteers themselves are not confident. None the less, performance is more than sufficient for scientific use; accuracy ranges from 77.4 per cent (spiral arm count) to 98.7 per cent (disc edge on). We observe some moderate confusion between similar answers, particularly between No or Weak bar, Moderate or Large bulges, and

¹⁵Corresponding to the typical ‘full’ retirement limit of approximately 40 classifications before discarding implausible classifications, see Section 4.3.1.

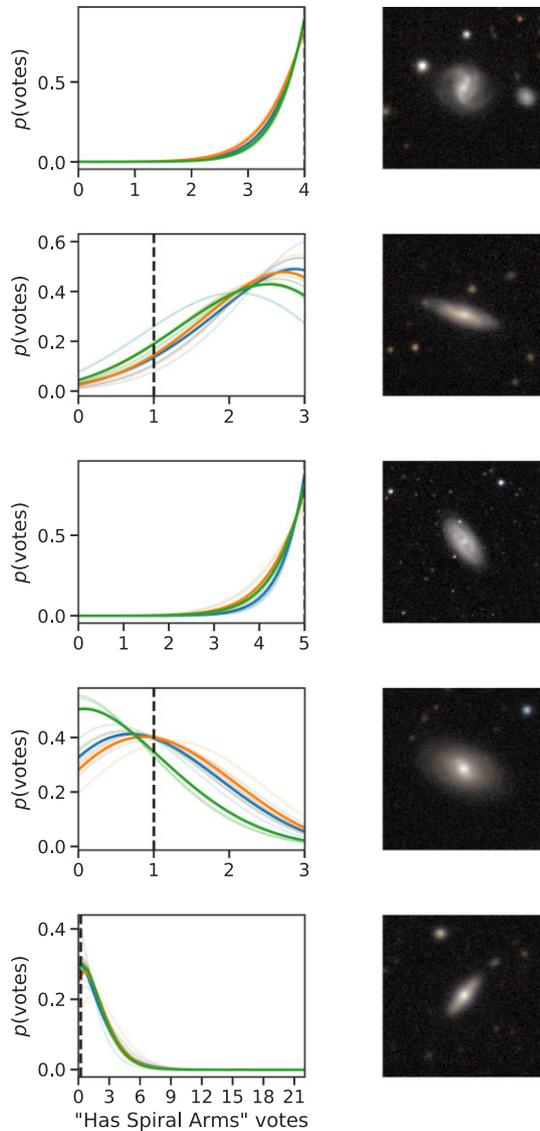


Figure 11. Posteriors for ‘Does this galaxy have spiral arms?’, split by ensemble model (bold colours) and, within each model, dropout forward passes (faded colours). The number of volunteers answering ‘Yes’ (not known to classifier) is shown with a black dashed line. Galaxies are selected at random from the test set, provided the spiral question is relevant (defined as a vote fraction of 0.5 or more to the preceding answer, ‘Featured’). The image presented to volunteers is shown to the right. The model input is a cropped, downsized, greyscale version (Section 5.1). The Dirichlet-Multinomial posteriors are strictly only defined at integer votes; for visualization only, we show the Γ -generalized posteriors between integer votes.

Two or Three spiral arms, which matches our intuition for the answers that volunteers might confuse and so likely reflects ambiguity in the training data. More surprisingly, there is also confusion between Two spiral arms and Can’t Tell. Fig. 14 shows random examples of spirals where the most common volunteer answer was Two, but the classifier predicted Can’t Tell, and vice versa. In both cases, the galaxies generally have diffuse or otherwise subtle spiral arms embedded in a bright disc, confusing both human and machine. This highlights the difficulty in using classification metrics to assess performance on ambiguous galaxies.

We can mitigate the ambiguity in classifications of galaxies by measuring regression metrics on the vote fractions, without rounding

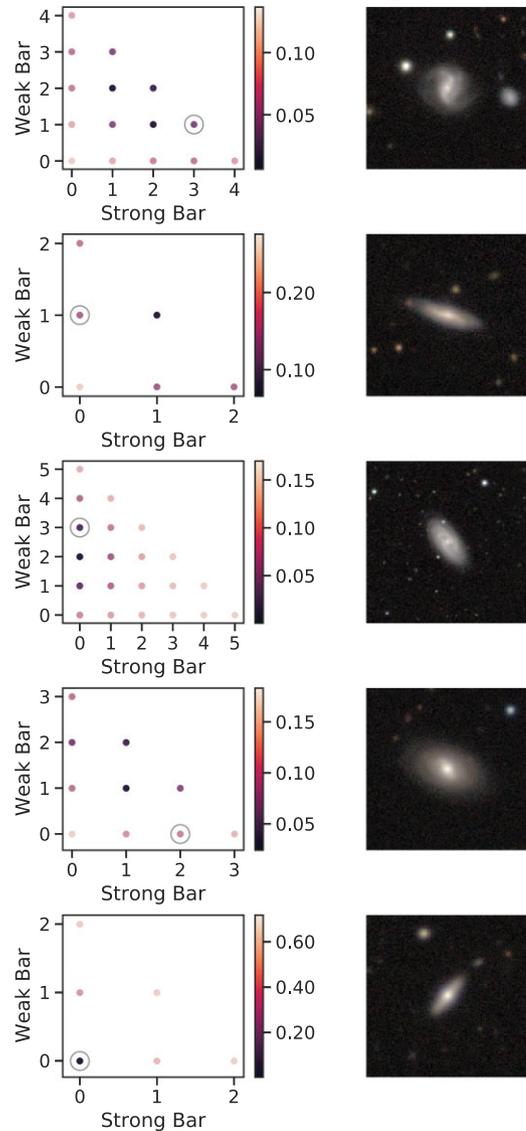


Figure 12. Posteriors for ‘Does this galaxy have a bar?’, for the same random galaxies selected in Fig. 11. Each point is coloured by the predicted probability of volunteers giving that many ‘Strong’, ‘Weak’, and (implicitly, as the total answers is fixed) ‘None’ votes. The volunteer answer (not known to classifier) is circled. For clarity, only the mean posterior across all models and dropout forward passes is shown.

to discrete classifications. Fig. 15 shows the mean deviations between the model predictions (mean posteriors) and the observed vote fractions, by question, for test set galaxies with approximately 40 volunteer responses. Performance is again excellent, with the predictions typically well within 10 per cent of the observed vote fractions. Predicting spiral arm count is relatively challenging, as noted above. Predicting answers to the ‘Merger’ question of ‘None’ (i.e. not a merger) is also challenging, perhaps because of the rarity of counter-examples.

The volunteer vote fractions against which we compare our predictions are themselves uncertain for most galaxies. We aim to predict the true vote fraction, i.e. the vote fraction from $\lim_{N \rightarrow \infty}$ volunteers, but we only know the vote fraction from N volunteers. However, 387 pre-active-learning galaxies were erroneously uploaded twice or more, and so received more than 75 classifications each. The vote fractions for these $N > 75$ galaxies will be very similar to the

Table 1. Classification metrics on all galaxies (above) or on galaxies where volunteers are confident for that question (i.e. where one answer has a vote fraction above 0.8). Multiclass precision, recall, and F1 scores are weighted by the number of true galaxies for each answer. Classifications on confident galaxies are near-perfect.

Question	Count	Accuracy	Precision	Recall	F1
(a) Classification metrics for all galaxies					
Smooth or featured	11346	0.9352	0.9363	0.9352	0.9356
Disc edge on	3803	0.9871	0.9871	0.9871	0.9871
Has spiral arms	2859	0.9349	0.9364	0.9349	0.9356
Bar	2859	0.8185	0.8095	0.8185	0.8110
Bulge size	2859	0.8419	0.8405	0.8419	0.8409
How rounded	6805	0.9314	0.9313	0.9314	0.9313
Edge on bulge	506	0.9111	0.9134	0.9111	0.8996
Spiral winding	1997	0.7832	0.8041	0.7832	0.7874
Spiral arm count	1997	0.7742	0.7555	0.7742	0.7560
Merging	11346	0.8798	0.8672	0.8798	0.8511
(b) Classification metrics for galaxies where volunteers are confident					
Smooth or featured	3495	0.9997	0.9997	0.9997	0.9997
Disc edge on	3480	0.9980	0.9980	0.9980	0.9980
Has spiral arms	2024	0.9921	0.9933	0.9921	0.9924
Bar	543	0.9945	0.9964	0.9945	0.9951
Bulge size	237	1.0000	1.0000	1.0000	1.0000
How rounded	3774	0.9968	0.9968	0.9968	0.9968
Edge on bulge	258	0.9961	0.9961	0.9961	0.9961
Spiral winding	213	0.9906	1.0000	0.9906	0.9953
Spiral arm count	659	0.9863	0.9891	0.9863	0.9871
Merging	3108	0.9987	0.9987	0.9987	0.9987

$\lim_{N \rightarrow \infty}$ true vote fraction limit, allowing us to accurately measure the mean vote fraction error of our machine learning predictions. We can also calculate the mean vote fraction error (versus the $N > 75$ vote fractions) from asking fewer ($N < 75$) volunteers by artificially truncating the number of votes collected, and ask – how many volunteer responses to that question would we need to have errors similar to that of our model? Note that the actual number of volunteers needed to be shown that galaxy to achieve an equivalent mean-squared error will be higher for questions only asked given certain previous answers (i.e. all but ‘Smooth or Featured?’ and ‘Merger?’), as some will give different answers to preceding questions and so not be asked that question. Fig. 16 shows the model and volunteer mean errors for a representative selection of questions; the model predictions are as accurate as asking that question to around 10 volunteers.¹⁶

We can also measure if our posteriors correctly estimate this uncertainty. As a qualitative test, Fig. 17 shows a random selection of galaxies binned by ‘Smooth or Featured’ vote fraction prediction entropy, measuring the model’s uncertainty. Prediction entropy is calculated as the (discrete) Shannon entropy $\sum_{\omega} p(\omega) \log(p(\omega))$ over all possible combinations of votes ω , assuming 10 total votes for this question (our results are robust to other choices of total votes). Unusual, inclined or poorly scaled galaxies have highly uncertain (high entropy) votes, while smooth and especially clearly featured galaxies have confident (low entropy) votes. The most uncertain galaxies (not shown) are so poorly scaled (due to incorrect estimation of the Petrosian radius in the NASA-Sloan Atlas) that they are barely visible. These results match our intuition and demonstrate that our posteriors provide meaningful uncertainties.

¹⁶The model is, in this strict sense, slightly superhuman.

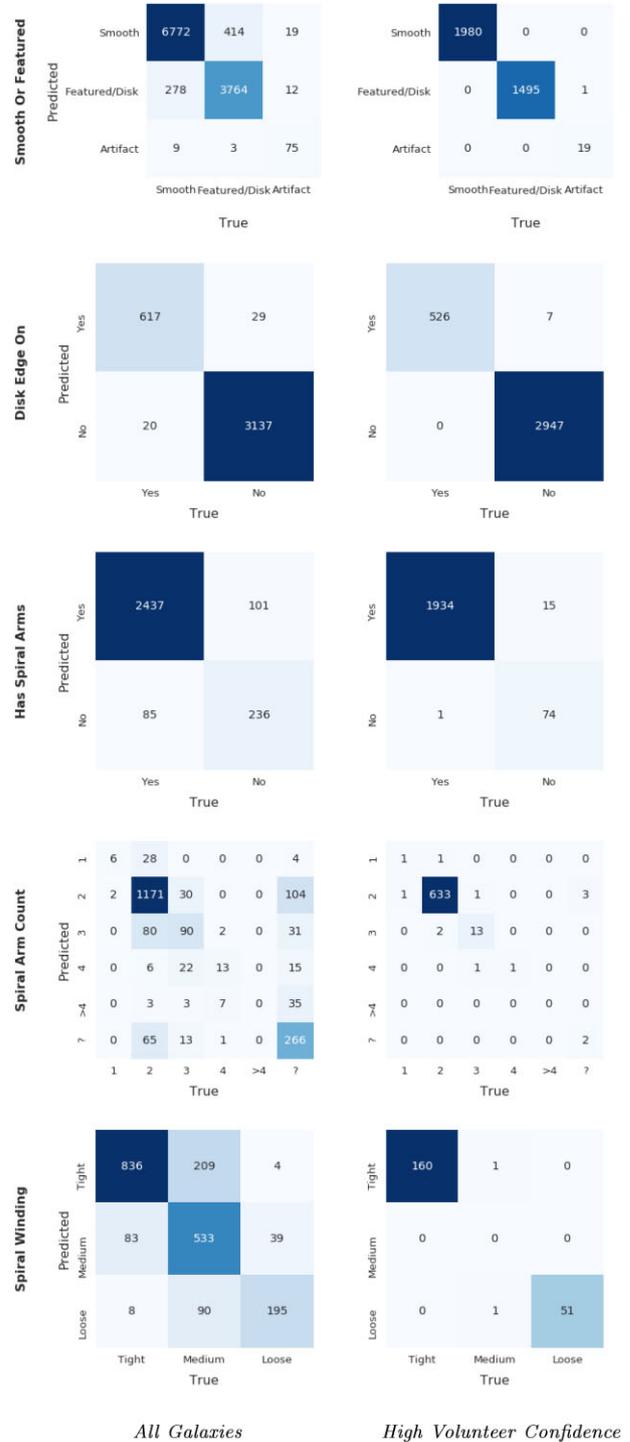


Figure 13. Confusion matrices for each question, made on the test set of 49 700 randomly selected galaxies with at least three volunteer votes. Discrete classifications are made by rounding the vote fraction (label) and mean posterior (prediction) to the nearest integer. The matrices then show the counts of rounded predictions (x -axis) against rounded labels (y axis). We report confusion matrices for all 49 700 galaxies (left-hand panel) and only for galaxies where the volunteers are confident in that question, defined as having the vote fraction for one answer above 0.8 (right-hand panel). Such confident galaxies are expected to have a clearly correct label, making correct and incorrect predictions straightforward to measure but also making the classification task easier. Continued below.

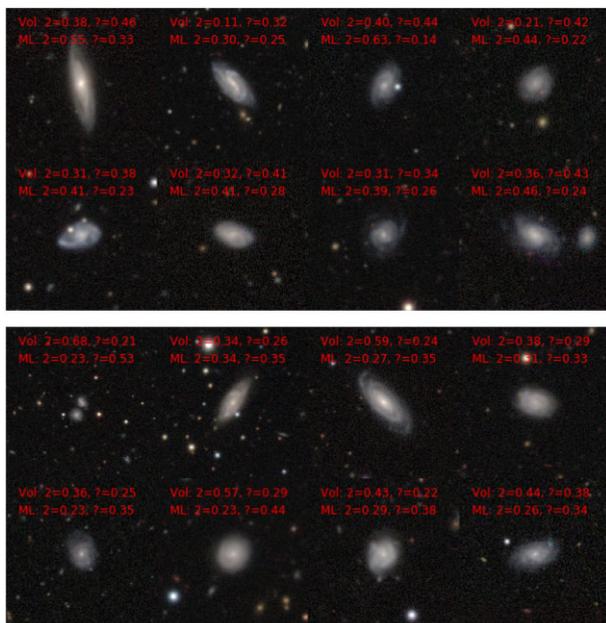


Figure 14. Random spiral galaxies where the classifier confuses the most likely volunteer vote for spiral arm count between ‘2’ and ‘Can’t Tell’. Above: galaxies where the classifier predicted ‘2’ but more volunteers answered ‘Can’t Tell’. Below: vice versa, galaxies where the classifier predicted ‘Can’t Tell’ but more volunteers answered ‘2’. Red text shows the volunteer (vol.) and machine-learning-predicted (ML) vote fractions for each answer. Counting the spiral arms is challenging, even for the authors. This highlights the difficulty in assessing performance by reducing the posteriors to classifications and then comparing against uncertain true labels.

More quantitatively, Fig. 18 shows the calibration of our posteriors for the two binary questions in GZD-5 – ‘Edge-on Disc’ and ‘Has Spiral Arms’. A well-calibrated posterior dominated by data (i.e. where the prior has minimal effect) will include the measured value within any bounds as often as the total probability within those bounds. We calculate calibration by, for each galaxy, iterating through each symmetric highest posterior density credible interval (i.e. starting from the posterior peak and moving the bounds outwards) and recording both the total probability inside the bounds and whether the recorded volunteer vote is inside the bounds. We then group (bin) by total probability and record the empirical frequency with which the votes lie within bounds of that total probability. In short, we are checking if, for all X , the observed value (vote fraction) falls within X per cent of the posterior interval X per cent of the time (Cook, Gelman & Rubin 2006; Levasseur, Hezaveh & Wechsler 2017). We find that calibration on these binary questions is excellent. Our classifier is correctly uncertain.

The ultimate measure of success is whether our predictions are useful for science. Masters et al. (2019; hereafter M19) used GZ2 classifications to investigate the relationship between bulge size and winding angle and found – contrary to a conventional view of the Hubble sequence – no strong correlation. We repeat this analysis using our (deeper) DECaLS data, using either volunteer or automated classification, to check if the automated classifications lead to the same science results as the volunteers.

Specifically, we select a clean sample of face-on spiral galaxies using M19’s vote fraction cuts of $f_{\text{feat}} > 0.43$, $f_{\text{hot-edge-on}} > 0.715$, and $f_{\text{spiral-yes}} > 0.619$. We also make a cut-off $f_{\text{merging}=\text{none}} > 0.5$, analogous to M19’s f_{odd} cut, to remove galaxies with ongoing mergers or with otherwise disturbed features. For the volunteer vote fractions,

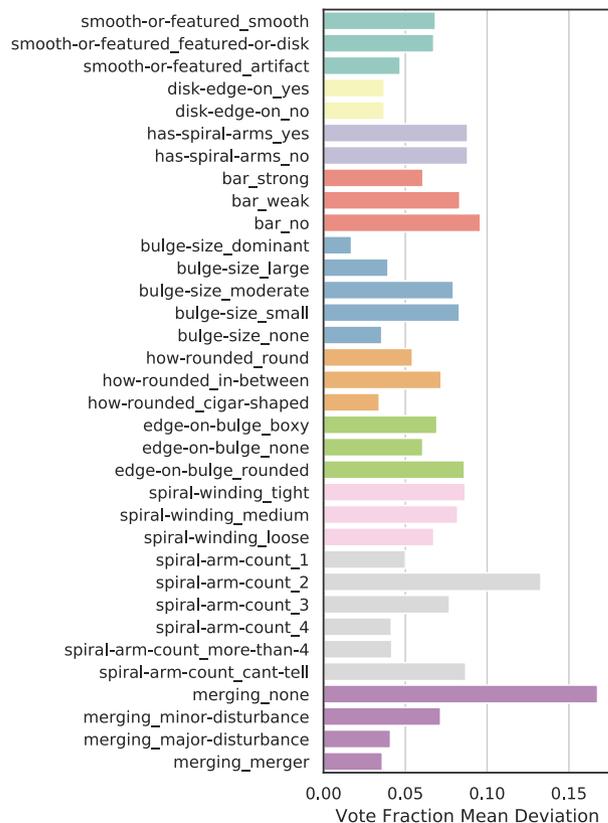


Figure 15. Mean absolute deviations between the model predictions and the observed vote fractions, by question, for the test set galaxies with approximately 40 volunteer responses. The model is typically well within 10 per cent of the observed vote fractions.

we can only use either GZD-1/2 or GZD-5 classifications, since the former decision tree had three bulge size answers and the latter had five; we choose GZD-5 to benefit from the added precision of additional answers. To avoid selection effects (Section 6.2) we only use galaxies classified prior to active learning being activated. For the automated classifications, we use a model trained on GZD-5 to predict GZD-5 decision tree vote fractions (including the five bulge answers) for every GZ DECaLS galaxy (313,798). This allows us to expand our sample size from 5378 galaxies using GZD-5 volunteers only to 43672 galaxies using our automated classifier.

We calculate bulge size and spiral winding following equations (1) and (3) in M19, trivially generalizing the bulge size calculation to allow for five bulge size answers:

$$W_{\text{avg}} = 0.5 f_{\text{medium}} + 1.0 f_{\text{tight}} \quad (8)$$

$$B_{\text{avg}} = 0.25 f_{\text{small}} + 0.5 f_{\text{moderate}} + 0.75 f_{\text{large}} + 1.0 f_{\text{dominant}}. \quad (9)$$

Both classification methods find no correlation between bulge size and spiral winding, consistent with M19. Fig. 19 shows the distribution of bulge size against spiral winding using either volunteer predictions (fractions) or the deep learning predictions (expected fractions) for the sample of featured face-on galaxies selected above. The distributions are indistinguishable, with the automated method offering a substantially larger (approx. 8X) sample size. We hope this demonstrates the accuracy and scientific value of our automated classifier.

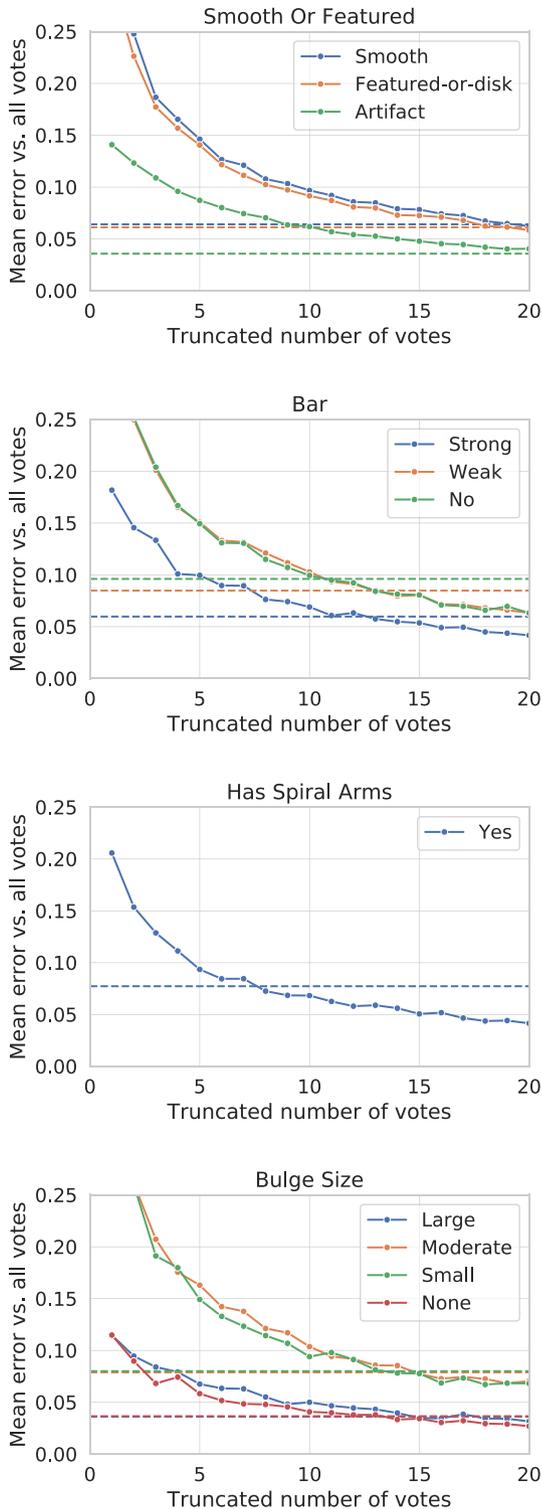


Figure 16. Mean error on the true ($N > 75$) vote fractions for either a truncated ($N = 0$ to $N = 20$) number of volunteers (solid) or the automated classifier (dashed). Asking only a few volunteers gives a noisy estimate of the true vote fraction. Asking more volunteers reduces this noise. For some number of volunteers, the noise in the vote fraction is similar to the error of the automated classifier, meaning they have a similar mean error versus the true vote fraction; this number is where the solid and dashed lines intersect. We find the automated classifier has a similar mean error to approx. 5 to 15 volunteers, depending on the question.

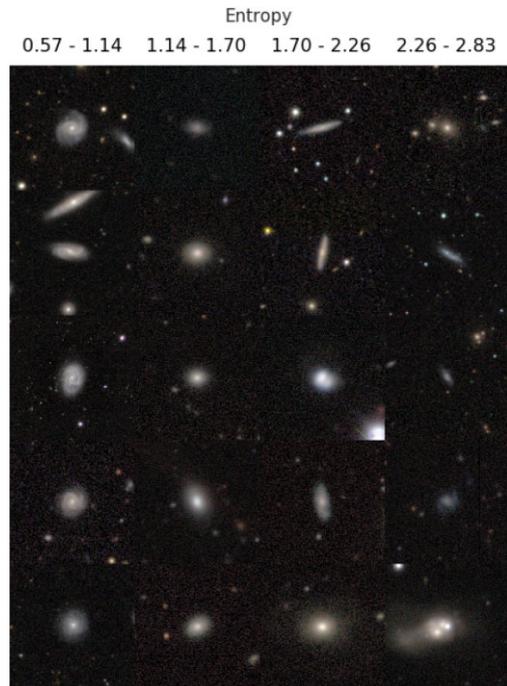


Figure 17. Galaxies binned by ‘Smooth or Featured’ vote prediction entropy, measuring the model’s uncertainty in the votes. Bins (columns) are equally spaced (boundaries noted above). Five random galaxies are shown per bin. Unusual, inclined, or poorly scaled galaxies have highly uncertain (high entropy) votes, while smooth and especially clearly featured galaxies have confident (low entropy) votes, matching our intuition and demonstrating that our posteriors provide meaningful uncertainties.

6 USAGE

6.1 Catalogues

We release two volunteer catalogues and two automated catalogues, available at <https://doi.org/10.5281/zenodo.4196266>.

`gz_decals_volunteers_ab` includes the volunteer classifications for 92 960 galaxies from GZD-1 and GZD-2. Classifications are made using the GZD-1/2 decision tree (Fig. A1). All galaxies received at least 40 classifications, and consequently have approximately 30–40 after volunteer weighting (Section 4.3.1). This catalogue is ideal for researchers needing standard morphology measurements on a reasonably large sample, with minimal complexity. 33 124 galaxies in this catalogue were also previously classified in GZ2; the GZD-1/2 classifications are better able to detect faint features due to deeper DECaLS imaging, and so should be preferred.

`gz_decals_volunteers_c` includes the volunteer classifications from GZD-5. Classifications are made using the improved GZD-5 decision tree which adds more detail for bars and mergers (Section 4.2). This catalogue includes 253 286 galaxies, but each galaxy does not have the same number of classifications. 59 337 galaxies have at least 30 classifications (after denoising), and the remainder have far fewer (approximately 5). The selection effects for how many classifications each galaxy receives are detailed below in Section 6.2. This catalogue may be useful to researchers who prefer a larger sample than `gz_decals_volunteers_ab` at the cost of more uncertainty and the introduction of selection effects, or who need detailed bar or merger measurements for a small number of galaxies. We use `gz_decals_volunteers_c` to train our deep learning classifier.

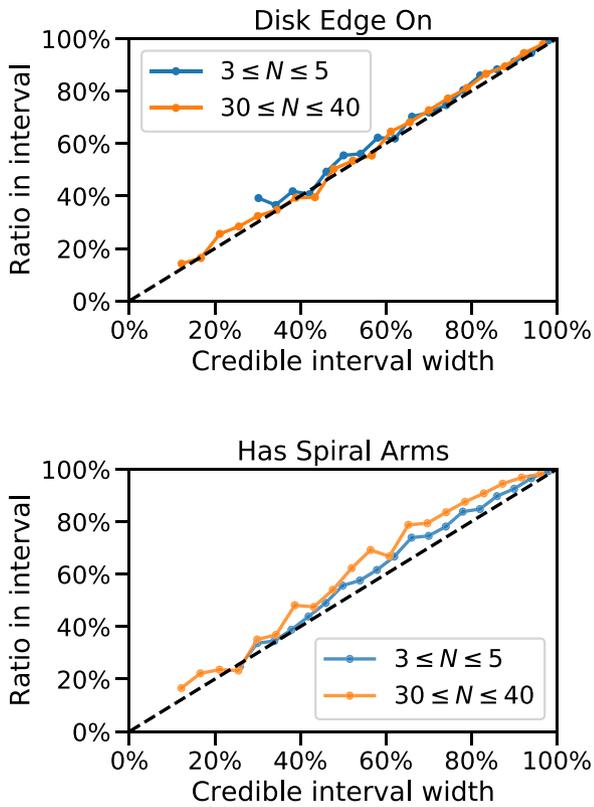


Figure 18. Calibration curves for the two binary GZ DECaLS questions. The x-axis shows the credible interval width – for data-dominated posteriors, roughly (e.g.) 30 per cent of galaxies should have vote fractions within their 30 per cent credible interval. The y-axis shows what percentage actually do fall within each interval width. We split calibration by galaxies with few votes (and hence typically wider posteriors) and more votes (narrower posteriors). Only credible intervals with at least 100 measurements are shown. Calibration for both questions is excellent.

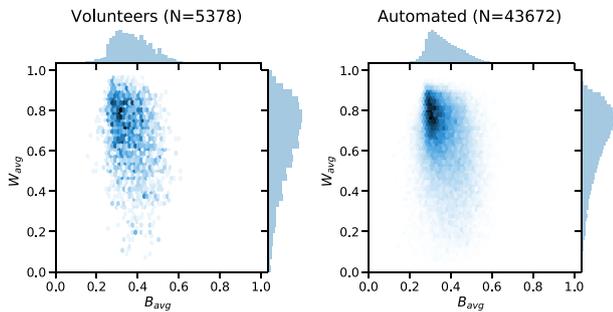


Figure 19. Distribution of bulge size versus spiral winding, using responses from volunteers (left-hand panel) or our automated predictions (right-hand panel). We observe no clear correlation between bulge size and spiral winding, consistent with M19. The distributions are consistent between volunteers and our automated method. We hope this demonstrates the accuracy and scientific value of our automated classifier.

The automated classifications are made using our Bayesian deep learning classifier, trained on `gz_decals_volunteers.c` to predict the answers to the GZD-5 decision tree for all GZ DECaLS galaxies (including those in GZD-1 and GZD-2). `gz_decals_auto_posteriors` contains the predicted posteriors for each answer – specifically, the Dirichlet concentration parameters

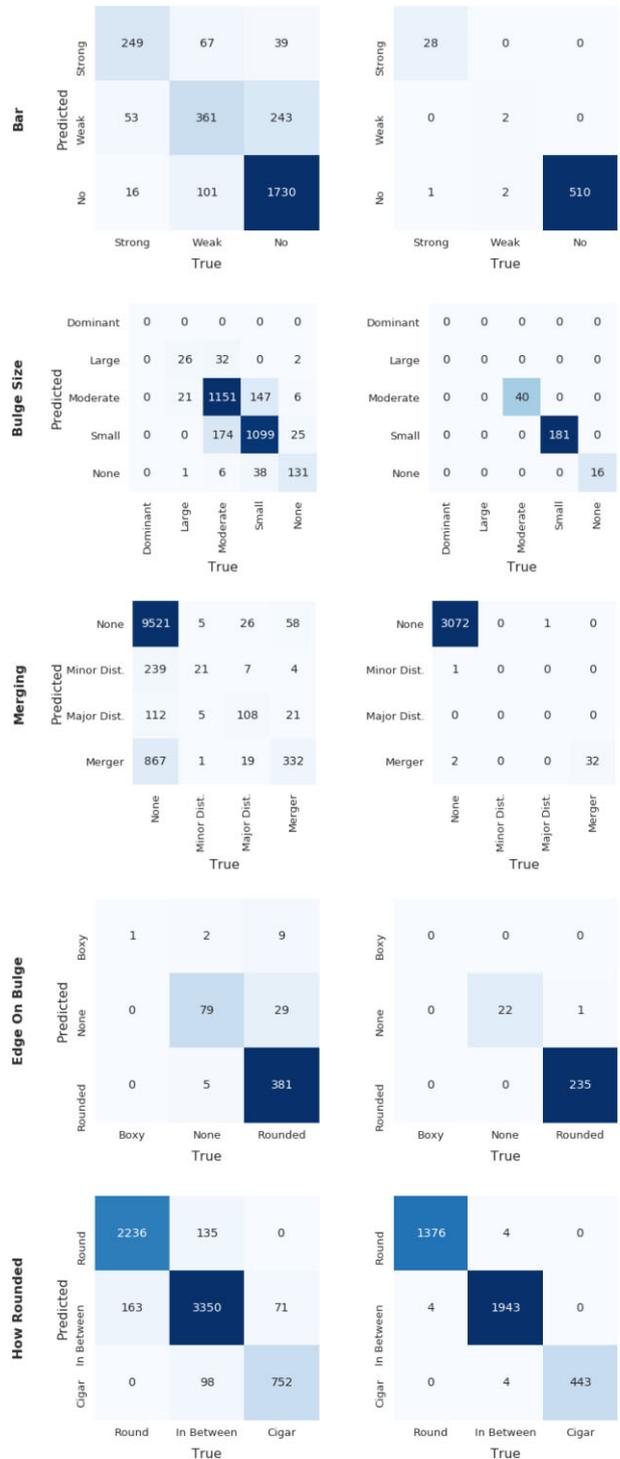


Figure 20. Confusion matrices, continued from above. To avoid the loss of information from rounding, we encourage researchers not to treat Galaxy Zoo classifications as discrete, and instead to use the full vote fractions or posteriors where possible.

that encode the posteriors. We hope this catalogue will be helpful to researchers analysing galaxies in Bayesian frameworks.

`gz_decals_auto_fractions` reduces those posteriors to the automated equivalent of previous Galaxy Zoo data releases, containing the expected vote fractions (mean posteriors). Note that not all vote fractions are relevant for every galaxy; we suggest assessing

relevance using the estimated fraction of volunteers that would have been asked each question, which we also include. We hope this catalogue will be useful to researchers seeking detailed morphology classifications on the largest possible sample, who might benefit from error bars but do not need full posteriors.

We also release Jupyter notebooks showing how to use each catalogue at <https://www.github.com/mwalmsley/zoobot>. These demonstrate how to load and query each catalogue with `pandas` (McKinney 2010), and how to create callable posteriors from the Dirichlet concentration parameters.

The automated catalogues may be interactively explored at https://share.streamlit.io/mwalmsley/galaxy-poster/gz_decals_mike_walmsley.py.

6.2 Selection effects for total classifications

The GZD-1/2 catalogue reports at least 40 classifications for all galaxies imaged by DECaLS DR1/2 and passing the appropriate selection cuts (Section 2.2). Additional classifications above 40 are assigned independently of the galaxy properties. The selection function for total classifications in the GZD-5 catalogue is more complex. In practice, if you require a strictly random sample of GZD-5 galaxies with more than five volunteer classifications, you should exclude galaxies where ‘random_selection’ is False. You may also consider using the posteriors from our deep learning classifier, which are comparable across all GZ DECaLS galaxies (Section 5). Below, we describe the GZD-5 total classification selection effects.

Early galaxies were initially uploaded row-by-row from the NASA-Sloan Atlas, each (eventually) receiving 40 classifications. We also uploaded two additional subsets. For the first, 1355 galaxies were targeted for classification to support an external research project. Of these, 1145 would have otherwise received five classifications. These 1145 galaxies with additional classifications are identified with the ‘targeted’ group and should be excluded. For the second, we reclassified the 1497 galaxies classified in both GZD-1/2 and the Nair & Abraham (2010) expert visual morphology classification catalogue to measure the effect of our new decision tree (results are shown in Section 4.2). Both the GZD-1/2 and GZD-5 classifications are reported in the respective catalogues (Section 6). Similarly to the targeted galaxies, 651 of these calibration galaxies would have otherwise received five classifications, are identified with the ‘calibration’ group, and should be excluded.

We then implemented active learning (Section 3.1), prioritizing 6939 galaxies from the remaining pool of 199 496 galaxies not yet uploaded. The galaxies are identified with the groups ‘active_priority’ (the galaxies identified as ‘most informative’ and selected for 40 classifications) and ‘active_baseline’ (the remainder). For a strictly random selection, both groups should be excluded, leaving the galaxies classified prior to the introduction of active learning.

Finally, we note that 14 960 (5.9 per cent) of GZD-5 galaxies received more than 40 classifications due to being erroneously uploaded more than once. The images are identical and so we report the aggregate classifications across all uploads of the same galaxy.

6.3 Suggested usage of vote fractions

The most appropriate usage of the Galaxy Zoo DECaLS vote fractions depends on the specific science case. Many galaxies have ambiguous vote fractions (e.g. roughly similar vote fractions for both disc and elliptical morphologies) because of observational limitations like image resolution, or because the galaxy morphology is truly in-between the available answers (perhaps because the galaxy has an

unusual feature such as polar rings, Moiseev et al. 2011, or because the galaxy is undergoing a morphological transition). To make best use of such galaxies, we recommend that, where possible, readers use the vote fractions as statistical weights in their analysis. For example, when investigating the differences in the stellar mass distributions of elliptical and disc galaxies, the disc (elliptical) vote fractions can be used as weights when plotting the distributions, resulting in the galaxies with the highest vote fraction for disc (elliptical) morphology dominating the resulting distribution. This ensures that each galaxy contributes to the analysis, without excluding galaxies with ambiguous vote fractions. For examples of using vote fractions as weights, see Smethurst et al. (2015) and Masters et al. (2019).

Using the vote fractions as weights is not appropriate for all science cases. For example, if galaxies of a particular morphology need to be isolated to form a sample for observational follow-up (e.g. overlapping pairs, see Keel et al. 2013, and ‘bulgeless’ galaxies, see Simmons et al. 2017a; Smethurst et al. 2019), or if the fraction of a certain morphological type of galaxy is to be calculated (e.g. bar fraction, see Simmons et al. 2014). These science cases require a cut on the appropriate vote fraction to be chosen. However, readers should be aware that making cuts on the vote fractions is a crude method to identify galaxies of certain morphologies and will result in an incomplete sample.

Table 2 shows our suggested cuts for populations of common interest, based on visual inspection by the authors and chosen for high specificity (low contamination) at the cost of low sensitivity (completeness). We urge the reader to adjust these cuts to suit the sensitivity and specificity of their science case, to add additional cuts to better select their desired population, and to make their own visual inspection to verify the selected population is as intended. For a full analysis, we once again suggest the reader avoid cuts by appropriately weighting ambiguous galaxies, or take advantage of the posteriors provided by our automated classifier.

7 DISCUSSION

What does a classification mean? The comparison of GZ2 and GZ DECaLS images (Fig. 6) highlights that our classifications aim to characterize the clear features of an image, and not what an expert might infer from that image. For example, volunteers might see an image of a galaxy that is broadly smooth, and so answer smooth, even though our astronomical understanding might suggest that the faint features around the galaxy core are likely indicative of spiral arms that would be revealed given deeper images. This situation occurs in several galaxies in Fig. 6. These ‘raw’ classifications will be most appropriate for researchers working on computer vision or on particularly low-redshift, well-resolved galaxies. The redshift-debiased classifications, which are effectively an estimate of galaxy features not clearly seen in the image, will be most appropriate for researchers especially interested in fainter features or studying links between our estimated intrinsic visual morphologies and other galaxy properties.

We showed in Section 4.2 that changing the answers available to volunteers significantly improves our ability to identify weak bars. This highlights that our classifications are only defined in the context of the answers presented. One cannot straightforwardly compare classifications made using different decision trees. Our scientific interests and our understanding of volunteers both evolve, and so our decision trees must also evolve to match them. However, only the last few years of volunteer classifications will use the latest decision tree (based on previous data releases), placing an upper limit on the number of galaxies with compatible classifications at any one time. Our automated classifier resolves this here by allowing us to retrospec-

Table 2. Suggested cuts for rough identification of galaxy populations, based on visual inspection by the authors. Q. votes is the minimum number of total votes for that question; for example, to identify strong bars, require at least 20 total votes to the question ‘Does this galaxy have a bar?’. This ensures enough votes to calculate reliable vote fractions. Assumes that all previous questions are filtered with the suggested cuts. For continuous measurements such as bulge size and spiral winding, we suggest combining all answers into a summary statistic like equation (8).

Population	Approx. Cut	Q. Votes	Notes
Featured disc	<code>featured > 0.7</code>	5	–
Disc	<code>featured > 0.3</code>	5	Will include featureless S0
Elliptical	<code>smooth > 0.7</code>	5	–
Edge-on disc	<code>yes > 0.8</code>	5	–
Not edge-on disc	<code>yes < 0.3</code>	5	–
Strong bar	<code>strong bar > 0.8</code>	20	–
Weak bar	<code>weak bar > 0.8</code>	20	–
Any bar	<code>strong bar + weak bar > 0.6</code>	20	–
Spiral arms	<code>spiral arms > 0.6</code>	20	–
No spiral arms	<code>spiral arms < 0.3</code>	20	Primarily ringed or irregular
Spiral count	<code>spiral count {n} > 0.75</code>	30	One-armed spirals are often mergers
Round edge-on bulge	<code>edge-on bulge rounded > 0.6</code>	10	–
Boxy edge-on bulge	<code>edge-on bulge boxy > 0.3</code>	10	Rare - visual inspection required
No edge-on bulge	<code>edge-on bulge none > 0.5</code>	10	–
Merger	<code>merger > 0.7</code>	10	–
Merger or overlap	<code>merger > 0.3</code>	10	To remove overlaps, redshifts or inspection required.
Post-merger	<code>major disturb. > 0.6</code>	10	–
Asymmetric or low surface brightness	<code>minor disturb. > 0.4</code>	10	–

tively apply the GZD-5 decision tree (with better weak bar detection, among other changes) to galaxies only classified by volunteers in GZD-1 and GZD-2. This flexibility ensures that Galaxy Zoo will remain able to answer the most pertinent research questions at scale.

We have shown (5.2) that our automated classifier is generally highly accurate, well-calibrated, and leads to at least one equivalent science result. However, we cannot exclude the possibility of unexpected systematic biases or of adversarial behaviour from particular images. Avoiding subtle biases and detecting overconfidence on out-of-distribution data remain open computer science research questions, often driven by important terrestrial applications (Szegedy et al. 2014; Hendrycks & Gimpel 2017; Eykholt et al. 2018; Smith & Gal 2018; Geirhos et al. 2019; Ren et al. 2019; Margalef-Bentabol et al. 2020; Yang et al. 2020). Volunteers also have biases (e.g. a slight preference for recognizing left-handed spirals; Land et al. 2008) and struggle with images of an adversarial nature (e.g. confusing edge-on discs with cigar-shaped ellipticals), though these can often be discovered and resolved through discussion with the community and by adapting the website.

We believe the future of morphology classification is in the thoughtful combination of volunteers and machine learning. Such combinations will be more than just faster; they will be replicable, uniform, error-bounded, and quick to adapt to new tasks. They will let us ask new questions – draw the spiral arms, select the bar length, separate the merging galaxies pixelwise – which would be infeasible with volunteers alone for all but the smallest samples (e.g. Lingard et al. 2020). And they will find the interesting, unusual, and unexpected galaxies which challenge our understanding and inspire new research directions.

The best combination of volunteer and machine is unclear. Our experiment with active learning is one possible approach, but (when compared to random selection) suffers from complexity to implement, an unknown selection function, and no guarantee – or even clear final measurement of – an improvement in model performance. Many other approaches are suggested in astrophysics

(Wright et al. 2017; Beck et al. 2018; Dickinson et al. 2019; Wright et al. 2019; Lochner & Bassett 2020; Martin et al. 2020) and in citizen science and human–computer interaction more broadly (Chang, Amershi & Kamar 2017; Bansal et al. 2019; Liu et al. 2020; Wilder, Horvitz & Kamar 2020). We will continue to search for and experiment with strategies to create the most effective contribution to research by volunteers.

8 CONCLUSION

We have presented Galaxy Zoo DECaLS; detailed galaxy morphology classifications for 311 488 galaxies imaged by DECaLS DR5 and within the SDSS DR11 footprint. The increased depth of DECaLS imaging allows us to better resolve faint morphological features than with previous Galaxy Zoo data releases using SDSS imaging (Fig. 5). Classifications were collected from volunteers on the Zooniverse citizen science platform over three campaigns, GZD-1, GZD-2, and GZD-5. GZD-5 used an improved decision tree (Fig. 4) aimed at best exploiting the deeper DECaLS images to identify weak bars, mergers, and tidal features.

All galaxies receive at least five volunteer classifications (Fig. 2). Galaxies in GZD-1 and GZD-2 receive at least 40. In GZD-5, two subsets receive 40: a random subset and a subset of galaxies prioritized as most likely to be informative for training machine learning models. These informative galaxies were identified following the method introduced by Walmsley et al. (2020) as the galaxies with the highest mutual information between model parameters and volunteer labels – intuitively, the galaxies on which several machine learning models confidently disagree.

Volunteer classifications were then used to train deep learning models to classify all galaxies. Our models are able to both learn from uncertain volunteer responses and predict full posteriors (rather than point estimates) for what volunteers would have said. This was achieved by interpreting the model predictions as the parameters for Dirichlet-Multinomial distributions and training to maximize

the corresponding likelihood (equation 6). We also approximate marginalizing over model weights (i.e. Bayesian deep learning) by training an ensemble of 5 models where each model makes predictions with MC Dropout. The resulting ensemble is accurate (Figs 13, 15, 16, and 20) and well-calibrated (Fig. 18).

We release both volunteer and automated classification catalogues at data.galaxyzoo.org. The volunteer catalogues include the total and mean volunteer responses for each question to each galaxy, and are split into the GZD-1/2 and GZD-5 campaigns (due to the modified decision tree). The automated catalogue includes predictions for every galaxy in any campaign. We share the predicted Dirichlet-Multinomial parameters that encode the full posteriors as well as the expected vote fractions that those posteriors imply. The expected vote fractions may be used in a similar manner to previous volunteer-only data releases, while the posteriors support more complex statistical analyses. We also provide guidance and code examples.

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This research made use of the open-source Python scientific computing ecosystem, including SCIPY (Jones et al. 2001), MATPLOTLIB (Hunter 2007), SCIKIT-LEARN (Pedregosa et al. 2011), SCIKIT-IMAGE (van der Walt et al. 2014), and PANDAS (McKinney 2010).

This research made use of ASTROPY, a community-developed core Python package for Astronomy (The Astropy Collaboration 2018).

This research made use of TENSORFLOW (Abadi et al. 2016).

The Legacy Surveys consist of three individual and complementary projects: the Dark Energy Camera Legacy Survey (DECaLS; NSF's OIR Lab Proposal ID # 2014B-0404; PIs: David Schlegel and Arjun Dey), the Beijing-Arizona Sky Survey (BASS; NSF's OIR Lab Proposal ID # 2015A-0801; PIs: Zhou Xu and Xiaohui Fan), and the Mayall z-band Legacy Survey (MzLS; NSF's OIR Lab Proposal ID # 2016A-0453; PI: Arjun Dey). DECaLS, BASS and MzLS together include data obtained, respectively, at the Blanco telescope, Cerro Tololo Inter-American Observatory, The NSF's National Optical-Infrared Astronomy Research Laboratory (NSF's OIR Lab); the Bok telescope, Steward Observatory, University of Arizona; and the Mayall telescope, Kitt Peak National Observatory, NSF's OIR Lab.

The Legacy Surveys project is honored to be permitted to conduct astronomical research on Iolkam Du'ag (Kitt Peak), a mountain with particular significance to the Tohono O'odham Nation.

The NSF's OIR Lab is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

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DATA AVAILABILITY

The data underlying this article are available via Zenodo at <https://doi.org/10.5281/zenodo.4196266>. This includes the galaxy morphology classifications from both volunteers and deep learning models, as well as the images uploaded to Galaxy Zoo. Any future data updates will be released using Zenodo versioning – please check you are viewing the latest version. The code underlying this article is available at <https://github.com/mwalmesley/zoobot>. We hope this code will be a useful resource for researchers looking to train their own deep learning models.

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SUPPORTING INFORMATION

Supplementary data are available at <https://doi.org/10.5281/zenodo.4196266>.

Appendix C. Example thumbnails of galaxies with confident automated classifications.

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APPENDIX A: GZD-1/2 DECISION TREE

Fig. A1 shows the Galaxy Zoo decision tree used for the earlier GZD-1 and GZD-2 DECaLS campaigns. This tree is based on the tree used for Galaxy Zoo 2 (Willett et al. 2013) with three modifications; the ‘Can’t Tell’ answer to ‘How many spiral arms are there?’ was removed, the number of answers to ‘How prominent is the central bulge?’ was reduced from four to three, and ‘Is the galaxy currently merging, or is there any sign of tidal debris?’ was added as a standalone question. Please see Section 3.2 for a full discussion.

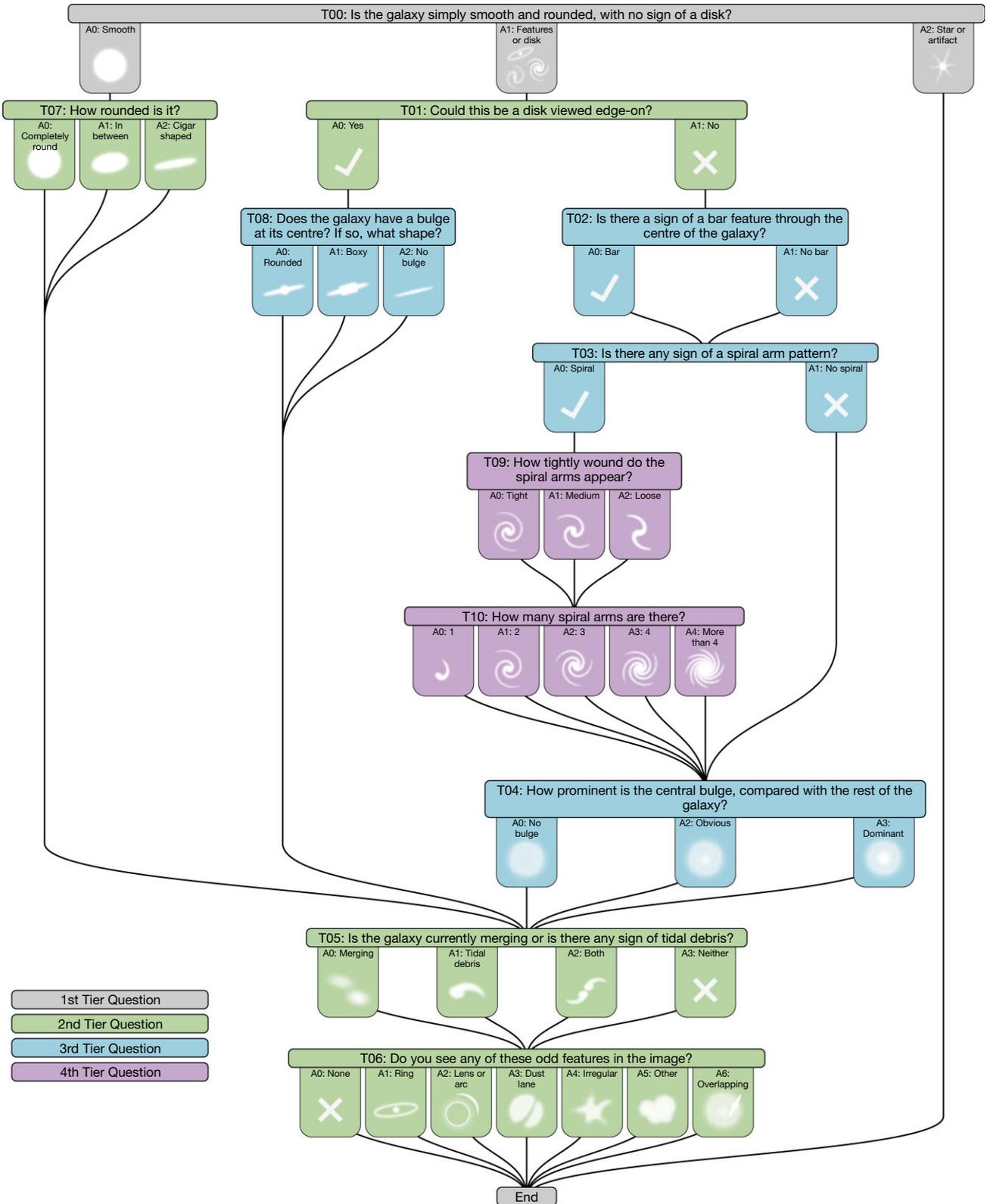


Figure A1. Decision tree used for GZD-1 and GZD-2, based on the Galaxy Zoo 2 decision tree. The GZD-5 decision tree is shown in Fig. 4.

APPENDIX B: CATALOGUE SAMPLE ROWS

Tables B1 and B2 present sample rows from the volunteer and automated morphology catalogues, respectively. The volunteer data shown is from GZD-5; the GZD-1/2 catalogue fol-

lows an equivalent schema. For brevity, we show only columns for a single question ('Bar') and a single answer ('Weak'); other questions and answers follow an identical pattern. A full description of all columns is available on data.galaxyzoo.org.

Table B1. Sample of GZD-5 volunteer classifications, with illustrative subset of columns. Columns: ‘iauname’ galaxy identifier from NASA-Sloan Atlas; RA and Dec, similarly; ‘Bar’ question total votes for all answers; ‘Bar’ question votes for ‘Weak’ answer; fraction of ‘Bar’ question votes for ‘Weak’ answer; estimated fraction after applying redshift debiasing (Section 4.3.2). Other questions and answers follow the same pattern (not shown for brevity). Full schema online at [this link](#).

iauname	ra	dec	bar_total-votes	bar_weak	bar_weak_fraction	bar_weak_debiased
J112953.88-000427.4	172.47	− 0.07	16	1	0.06	0.15
J104325.29+190335.0	160.86	19.06	2	0	0.00	0.00
J104629.54+115415.1	161.62	11.90	4	2	0.50	–
J082950.68+125621.8	127.46	12.94	0	0	–	–
J122056.00-015022.0	185.23	− 1.84	3	0	0.00	–

Table B2. Sample of automated classifications (GZD-5 schema), with illustrative subset of columns. Columns: ‘iauname’ galaxy identifier from NASA-Sloan Atlas; RA and Dec, similarly; proportion of volunteers estimated to be asked the ‘Bar’ question (i.e. the product of the preceding vote fractions) for estimating relevance; Dirichlet concentrations defining the predicted posterior for the ‘Bar’ question and ‘Weak’ answer (see Section 5); predicted fraction of ‘Bar’ question votes for the ‘Weak’ answer derived from those concentrations. Other questions and answers follow the same pattern (not shown for brevity). Full schema online at [this link](#).

iauname	RA	Dec	bar_proportion_asked	bar_weak_concentrations	bar_weak_fraction
J112953.88-000427.4	172.47	− 0.07	0.14	[6.158, 5.0723, 5.4842,...	0.09
J104325.29+190335.0	160.86	19.06	0.13	[4.3723, 4.5933, 4.8582...	0.07
J100927.56+071112.4	152.36	7.19	0.58	[9.3129, 10.3911, 8.4791...	0.40
J143254.45+034938.1	218.23	3.83	0.55	[13.2981, 12.2639, 8.8957...	0.26
J135942.73+010637.3	209.93	1.11	0.77	[15.6247, 15.6893, 14.72....	0.28

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