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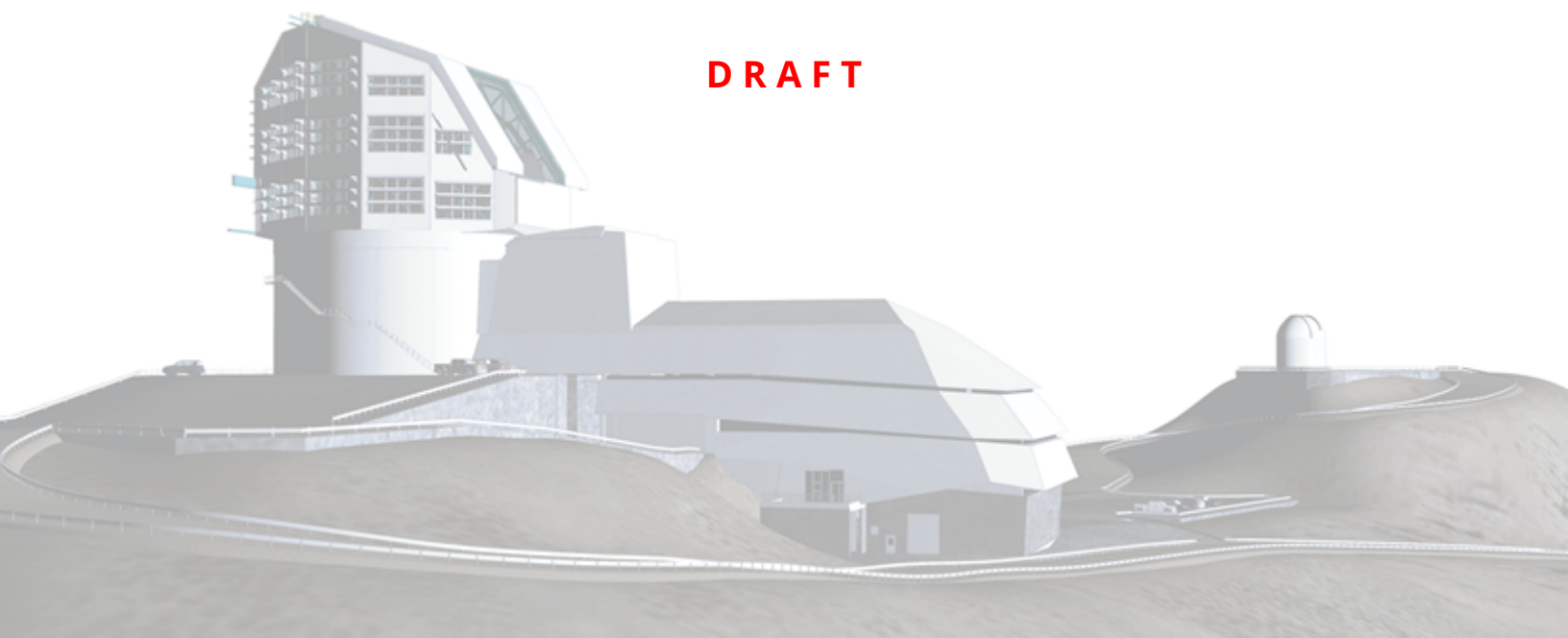
Vera C. Rubin Observatory
Data Management

A Roadmap to Photometric Redshifts for the LSST Object Catalog

M. L. Graham, J. Bosch, L. P. Guy,
and the DM System Science Team.

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D R A F T

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Abstract

This roadmap guides the Rubin Observatory Data Management (DM) team's efforts to engage with the scientific community in order to select, implement, and validate the photometric redshift (photo-z) estimator(s) in the Data Release (DR) processing pipeline, and serve the resulting photo-z data products for the DR `Object` catalog. This is a ***living document*** that will evolve over time to incorporate input from the science community (including the Science Collaborations), which has a considerable wealth of expertise in generating photo-z catalogs and will be the primary users of the photo-z data product.

This roadmap proposes three phases for the DM team:

- **Phase 0:** Finalize this plan and its timeline (Dec 31 2020).

- **Phase 1:** Define the criteria for evaluating photo-z estimators (Aug 31 2021) by soliciting community input regarding their science needs and interests.

- **Phase 2:** Prepare a ranked list of community-vetted photo-z estimator(s) by soliciting community "letters of recommendation" (due Apr 31 2022).

- **Phase 3:** Facilitate community participation in a "Photo-z Validation Cooperative" that will analyze photo-z estimates based on commissioning data, which will inform DM's selection of community-vetted photo-z estimator(s) for DR1.

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Change Record

Version	Date	Description	Owner name
1	2017-04-01	Initial release of preliminary investigation.	Melissa Graham
2	2018-10-16	Edited to align with recent DPDD updates, some of which were based on the recommendations of Version 1 of this document.	Melissa Graham
3	2020-XX-XX	Updated as per ticket/DM-6367.	Melissa Graham

Contents

A Roadmap to Photometric Redshifts for the LSST `Object` Catalog

1 Introduction

A *photometric redshift* is an estimate of an object's cosmological redshift which is based on its photometry (e.g., apparent magnitudes in multiple filters) instead of on its spectral features (e.g., emission and absorption lines). Redshift is a key component of many science goals that will be pursued with data from the Legacy Survey of Space and Time (LSST). Since it will be impossible to obtain spectra for the billions of galaxies that LSST will observe, photometric redshift estimates will be necessary.

Typically, photometric redshift estimators either fit template spectra to the observed photometry or match photometry to a training set of galaxies with spectroscopic redshifts. The latter is often done with machine learning codes, and hybrid photo-z estimators also exist. Some photo-z estimators are more appropriate for some science goals than others, due to the quality or type of results they produce (e.g., point estimates, full posterior probability density functions, or redshift distributions in tomographic bins). For this reason, several research groups in the science community are already planning to generate multiple kinds of photo-z (e.g., the Dark Energy Science Collaboration).

It would be scientifically prohibitive if all users of LSST data had to generate their own photo-z estimates, as this is a computationally intensive calculation. Furthermore, it is a requirement that the LSST Data Management System (DMS) calculate photo-z and store them in the `Object` catalog. Research and development of new photometric redshift algorithms for LSST data is beyond the scope of DM (i.e., not part of DM's specialized knowledge base), as it is an active area of current and future LSST research. The high-level plan is that one or more existing photo-z estimator(s) be installed into the Data Release (DR) pipeline and run at scale, and/or a user-generated photo-z catalog be ingested and federated with the `Object` catalog.   DMS-REQ-0046

This roadmap guides the Rubin Observatory DM team's engagement of the scientific community regarding a decision on which *community-vetted* photo-z estimator(s) will be implemented for the DR1 `Object` catalog. This is a ***living document*** that will evolve over time to incorporate input from the science community, which has a considerable wealth of expertise in generating photo-z catalogs and will be the primary users of the photo-z data product.

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2   Proposed Roadmap and Timeline

All items in this timeline reference *actions taken by the Data Management team*. A diagram representing this proposed timeline is provided in Figure 1.

Several alternative options for the generation of `Object` catalog photo-z, such as photo-z as in in-kind contribution from an international partnership, or federating a user-generated catalog, are briefly discussed in Appendix A.

In the subsections below, several terms are used, for which we provide clarification here. **Advertise broadly** means posting to Community.lsst.org, sending emails to Science Collaborations and other lists of potentially interested individuals (e.g., authors of papers containing the terms LSST and photo-z), and including in Rubin newsletters. The **community** or **science community** refers to any individuals or groups who plan to use Rubin data products or services for science (and in the particular case of this document, use the `Object` catalog photo-z). **LSST Photo-z Forums** are proposed as a means of facilitating community-project interaction and soliciting input. These forums will be informal discussions, open to all, and held virtually at a variety of times so as to enable participation from all timezones. The forums would *not* be the only way to contribute – community input will also be ingested to this document from, e.g., written postings on Community.lsst.org.

2.1   Phase 0: Finalize Roadmap and Timeline

Sep 30 2020: Merge the branch `tickets/DM-6367` of this document to master. Write a solicitation for community input on the roadmap and timeline, and advertise it broadly.
Nov, Dec 2020: Hold two LSST Photo-z Forums that focus on gathering project and community input on the proposed roadmap and its timeline.
Dec 31 2020: Incorporate community input into § 2 of this document.

2.2   Phase 1: Define the Minimum Attributes and Evaluation Criteria

Jan 1 2021: Write a solicitation for community input on the minimum attributes (§ 3) and evaluation criteria (§ 4) and advertise it broadly.
Feb – Jun 2021: Hold three LSST Photo-z Forums that focus on gathering project and community input on the proposed minimum attributes and evaluation criteria.

mid-Aug 2021: During the Rubin 2021 Project and Community workshop, hold a breakout session to collect any remaining input and discuss the evaluation criteria.

Aug 31 2021: Incorporate community input into § 3 and § 4 of this document.

2.3 Phase 2: Prepare a Ranked List of Candidate Photo-z Estimators

Sep 1 2021: Write a call for "Letters of Recommendation" from the science community that advocate for particular photo-z estimators (draft in § 5), and advertise it broadly.

Nov 2021 – Apr 2022: Hold four LSST Photo-z Forums that focus on allowing the project and the community discuss the various features, merits, or drawbacks photo-z estimators.

Apr 31 2022: Acceptance deadline for scientific "Letters of Recommendation".

Jun 30 2022: Choose a shortlist of community-vetted estimators to consider during Phase 3, and add the rationale for these choices to § 5.1.

2.4 Phase 3: Facilitate the Photo-z Validation Cooperative

During commissioning, the DM team will facilitate community participation in a "Photo-z Validation Cooperative", which will analyze photo-z estimates from the shortlisted estimators based on commissioning data. The timeline for this effort remains to be determined, as it is contingent on the commissioning schedule. The DM team will make any final decisions regarding which photo-z estimator(s) will be used for DR1 *after* this effort. See § 6 for a preliminary description of the cooperative.

2.5 Rubin Operations

During operations, the Data Production team will produce and validate photo-z for the `Object` catalog using the software and data products delivered by the Construction-era DMS (which is likely to include in-kind contributions, described below). These photo-z for the `Object` catalog will be available at the time of all data releases, starting with DR1, along with any and all supporting materials such as documentation or spectral templates. The Rubin Operations team may solicit and collect community feedback on the photo-z performance, and return to any stage of this process to update the attributes, algorithms, implementation, and/or validation of `Object` catalog photo-z for future data releases.

2.6   International Partnerships (In-Kind Contributions)

At all stages of this photo-z roadmap, in-kind program contributions related to photo-z should be included and integrated into the communal efforts to optimize the LSST photo-z. These contributions might include, e.g., individuals' expertise; scientific analyses; software algorithms, tools, or infrastructure; computational resources; datasets or observing time. These contributions might be directed to the Project (e.g., DM, commissioning team), and/or to the science community (e.g., a Science Collaboration, all data rights holders).

In-kind teams should expect to work closely with the project (e.g., DM) and other Rubin community members on each step of this proposed roadmap, including the solicitation of input from the science community, the process of implementation and validation, and maintaining and evolving their contributions during Rubin Operations (as applicable). In-kind contributors should also review the summary of related data products and documentation that might pertain to their contribution (Appendice C and E), and the example scientific use-cases that the photo-z estimates are expected to support (Appendix D). For in-kind programs making photo-z related contributions to the project, a Photo-z In-Kind Program Coordination (IPC) group exists to facilitate communications (point of contact: Melissa Graham).

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Proposed Photo-z Roadmap for DM
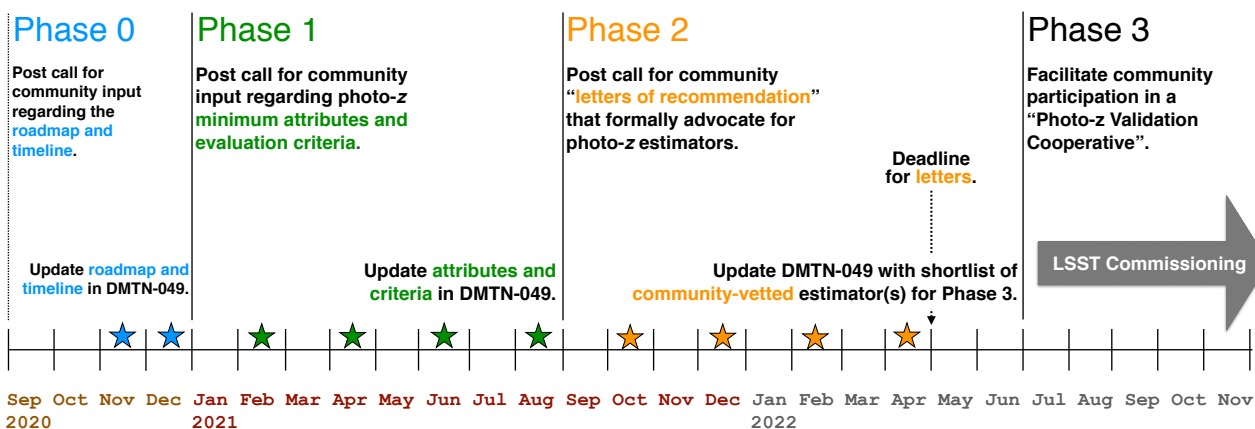
FIGURE 1: A schematic of the proposed timeline in § 2. In addition to the virtual forums (stars), community input will be ingested from discussions on Community.lsst.org.

3 Proposed Minimum Attributes

Community input on these proposed minimum attributes of `Object` **catalog photo-z are solicited during Phase 1 (§ 2.2),** as is input on the supporting material in Appendices C and D. This section will be updated to reflect community input prior to Phase 2.

The following *preliminary* definitions for the photo-z attributes are based on the guiding principle that the DMS-generated `Object` photo-z should, at minimum, *meet the basic science needs for communities which will not or cannot generate custom photo-z* and also DM's internal use-cases (Appendix D).

A *basic* science need would not include, for example, photo-z of the quality required for major cosmological advances. The development of such photo-z algorithms is an active research topic within the Dark Energy Science Collaboration [21], and a significant effort which the Rubin Observatory staff should not (and could not) attempt to replicate.

Type of Estimator – The `Object` catalog photo-z estimates should be based on a template-fitting algorithm *and then also* a machine-learning algorithm, if multiple results can be stored (see Appendix C.4). The main motivation for this is galaxies-related science (Appendix D.2.3) and internal (Appendix D.1) use-cases, which would use the best-fit template to derive additional galaxy properties.

Output Format – The `Object` catalog photo-z should include the posterior distribution function and a point estimate with an uncertainty, as well as reliable uncertainties and/or flags to help the novice user avoid misinterpreting the results or overestimating their significance. For template-fit photo-z results, an identifier for the best-fit template should be provided, and those templates be made publicly accessible. A list of the photo-z outputs (and associated documentation) is put forth in Appendix C.3.

Performance – Based on the science use-cases in Appendix D, the `Object` catalog photo-z could have a point-estimate accuracy of $\sim 10\%$ and still meet the basic science needs. The photo-z results should result in a standard deviation of $z_{\mathrm{true}} - z_{\mathrm{phot}}$ of $\sigma_z < 0.05(1 + z_{\mathrm{phot}})$, and a catastrophic outlier fraction of $f_{\mathrm{outlier}} < 10\%$, over a redshift range of $0.0 < z_{\mathrm{phot}} < 2.0$ for galaxies with $i < 25$ mag galaxies.

4 Proposed Evaluation Criteria

Community input on this proposed evaluation criteria for photo-z estimators is solicited during Phase 1 (§ 2.2), as is input on the supporting material in Appendices B, C, and D. This section will be updated to reflect community input prior to Phase 2.

These criteria will guide the community's "Letters of Recommendation" in Phase 3 (§ 5), DM's eventual selection of photo-z estimator(s) to implement for DR1, and would also apply to any user-generated catalogs to be federated with the `Objects` table (Appendix A.1).

Meeting the Defined Minimum Attributes – Estimators should meet the minimum attributes defined in § 3, and serve at least the basic science needs of the community and any internal DM use-cases (Appendix D). The preliminary proposed performance (in version 3 of this document) has been shown to be achievable for simulated LSST data with existing photo-z estimators [e.g., 9, 18]. The criteria for evaluating performance overlaps with the validation tests discussed in Appendix B.2, and evaluating the performance of potential photo-z estimators with LSST data will be part of the validation process based on commissioning data (Phase 3; § 5).

Scientific Utility and User Experience – Photo-z estimators should serve as wide a variety of science needs as possible (Appendix D). It is beneficial if estimators have demonstrated success with other wide-field optical surveys, especially for surveys that overlap with LSST (for results comparisons), and have broad community adoption. The estimators' data products should be straightforward to understand and easy to access (described further in Appendix C.3). Estimators should have detailed, publicly accessible documentation (e.g., a journal article, a website, a schema) to facilitate community use.

Implementation, Validation, and Computational Requirements – The photo-z estimators implementation process (Appendix B) should be straightforward; the estimator must be able to be integrated with the DR pipelines. New algorithmic development is beyond the scope of DM, and the estimators should not need any expansion or maturation prior to installation in the DMS. Estimators should take as inputs quantities that the LSST pipelines are planning to produce (Appendix C.1). The necessary data – from LSST or elsewhere – for training, calibration, and validation must exist during the preparation of DR1 (e.g., galaxy catalogs with spectroscopic redshifts and LSST photometry; Appendix C.2). The computational needs of the estimator must fit within the available resources of the data facility.

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5   Proposed Call for Photo-z "Letters of Recommendation"

This draft will be updated based on community input ingested to § 3 and 4 during Phase 1. Community input on this proposed draft call for letters of recommendation is welcome at any time.

Draft: The Rubin Observatory LSST DM team solicits letters of recommendation from the science community that advocate for particular photo-z estimators, based on the evaluation criteria defined in § 4. The DM team's goal is to create a shortlist of several community-vetted photo-z estimator(s) that will serve as broad a range of LSST science goals as possible and also meet internal (DM use-case) requirements. The shortlisted estimators would then be supported by DM during the "Photo-z Validation Cooperative", which will be based on commissioning data (§ 6). These letters should not be seen as a competition, but rather as a formal chance for the science community to state their scientific needs regarding `Object` catalog photo-z. These letters should focus on providing a clear and scientifically-justified prioritization of photo-z estimators that is informed by the evaluation criteria in § 4. Letters could focus on many, a few, or just one estimator(s) or science goal(s). Letters could be *qualitative* in their evaluation of the photo-z estimators, or could include *quantitative* analyses of simulated LSST data, or data from other facilities.

5.1   Rationale for DM's Shortlisted Photo-z Estimator(s)

TBD: this section will describe which community-vetted photo-z estimator(s) DM has shortlisted for the photo-z validation cooperative, and why.

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6   Proposed Photo-z Validation Cooperative

As the scientific community has a considerable wealth of expertise in generating photo-z catalogs, and will be the primary users of the photo-z data product, it is essential that the validation process includes their input. Towards this end the DM team plans to facilitate a "Photo-z Validation Cooperative" to analyze photo-z estimates based on LSST commissioning data.

Draft: Functionally this may be similar to a data challenge, but should not be though of as a competition that results in a "winning" estimator. Rather, it will serve as a collaborative endeavor between project and community to maximize the scientific utility of the `Object` catalog photo-z data products. **It is anticipated that this process will start with open communication about what the science community needs, in terms of commissioning data and access to tools and computational resources, to fully participate in the photo-z co-op.** During this process, DM will focus on providing technical support for the validation of the photo-z estimators shortlisted based on the community's letters of recommendation (§ 5), but the community may also consider estimator(s) that were not shortlisted.

Types of commissioning data that might be most useful for scientific validation of photo-z estimators are described in § 6.1. A preliminary collection of photo-z validation techniques based are presented in Appendix B. Documentation regarding the technical aspects of DM's implementation and validation process is considered beyond the scope of this document and will appear elsewhere.

6.1   Potential Commissioning Data for Photo-z Validation

The commissioning surveys and their schedule remained subject to change; the examples below will be updated in the future as the situation clarifies.

Data Preview 1 (DP1): The first phase of commissioning with ComCam might include, e.g., tests of the scheduler; tests of image quality, depth, astrometry, and photometry; and a 20-year depth test to stack images over a range of conditions [LSE-79]. DP1 might be useful as preliminary test data during the implementation of the photo-z estimators, and help to test the formats of the input and output data, create visualizations for the validation codes, etc.

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Data Preview 2 (DP2): The second phase of commissioning with the Science Camera might include, e.g., wide area surveys to the full 10-year depth in addition to a 20-year depth stack and tests of image quality, as in DP1 [LSE-79]. DP2 is more likely to provide the data set for photo-z validation, and also some of the needed training data for LSST photo-z described in Appendix C.2.

As a side note for LSST users who are interested in doing science with commissioning data: it should not be assumed that any release of data products based on commissioning surveys will include photo-z estimates. The release of any photo-z catalogs prior to DR1 remains at the discretion of the DM team.

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A Appendix: Options for `Object` Catalog Photo-z

A.1 Federation of a User-Generated Photo-z Catalog

The DMS as delivered to the Operations Project will provide photo-z with a level of scientific capability defined by § 3. If those photo-z are rendered obsolete by community efforts, and a superior user-generated photo-z catalog is validated, *and* its creators are willing to share, then this data product should be ingested ("federated") and served with the `Object` catalog.

To facilitate this option might require providing the community team(s) with access to data release previews[1] so that they may train and calibrate their photo-z estimator, and minimize the time between data release and federation of a new photo-z catalog to the `Objects` table. Facilitating multiple teams sharing their photo-z catalogs might involve hosting a "photo-z server" within the Rubin Science Platform. For example, the Dark Energy Survey's Science Portal is an infrastructure for organizing input catalogs, installing photo-z estimators, training and running them, and evaluating their output[2], as described by Gschwend et al. [10]).

A.2 The Science Impacts of a Data Release Without `Object` Photo-z

The option to federate a community-generated photo-z catalog leads to this question: *If there will likely be a superior community photo-z anyway, should Data Management avoid installing a photo-z estimator in the DMS, and instead simply wait for the community to generate a catalog?* There are several significant risks and drawbacks to this option.

- An `Object` table without photo-z at the time of data release is a problem for brokers, unless alerts are instead (or additionally) associated to an older DR's `Object` catalog that has photo-z. Brokers require host-galaxy photo-z to optimally classify and prioritize transients for follow-up, and plan to obtain this information via each alert's associations with nearby `Objects` from *the most recent DR*.

- The `Object` photo-z might be tailored to the specific science case of the community team and might not serve the broader science use-cases.

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[1]Data release previews are envisioned to be some small, e.g., $\sim 10\%$, amount of a data release made available early, e.g., weeks to months, before the full release to enable community feedback and preparations prior to the full release.

[2]A series of YouTube tutorials about the DES Science Portal are available at `https://www.youtube.com/playlist?list=PLGFEWqwqBauBIYa8H6KnZ4d-5ytM59vG2`.

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- There is no initiative or reward for the community team which has generated the photo-z, except perhaps citations to their photo-z catalog.

- There would be no `Object` photo-z if no community team generates and donates a catalog, which is a risk for the science use-cases described in Appendix D.2

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B   Implementation and Validation

B.1   An Example Implementation Process

For reference, the basic steps for implementing a photo-z estimator include:

- prepare the LSST data inputs to the photo-z estimators (Appendix C.1)

- prepare the training and calibration data (Appendix C.2)

- install the needed codes (a technical aspect to be described elsewhere)

- run the estimator (on its own and/or embedded in the data release pipeline)

- validate the photo-z estimator outputs (below, B.2)

- store the results in the `Object` catalog (Appendices C.3 and C.4)

- ensure output schema and access methods are documented (Appendix C.3)

B.2   Example Validation Tests

For reference, this section describes some photo-z validation tests, some of which overlap with the evaluation criteria described in § 4. Validation tests and quality assessment diagnostics will be necessary to ensure the results meet performance expectations (§ 3). These lists are based in part on a brainstorming session during the LSST Project and Community Workshop's session on Photometric Redshifts on Aug 14 2019[3].

Journal articles that demonstrate validation processes for photo-z from multi-band wide-area surveys include *"DES science portal: Computing photometric redshifts"* [10]; *"Photometric redshifts for Hyper Suprime-Cam Subaru Strategic Program Data Release 1"* [20]; and *"On the realistic validation of photometric redshifts"* [1].

Truth Comparisons – Catalogs of true redshifts can be obtained by withholding some fraction of the training set or by cross-matching to external spectroscopic catalogs. Validation metrics should include at least those used to define the minimum performance of the LSST photo-z for basic science needs (§ 3). A list of potential metrics might include the following,

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[3]E.g., slide 14 of `https://docs.google.com/presentation/d/1GEahvDQXIjSL4lLVjDlZHV5zpXLhGQfHwVtucs72Ajg/edit?usp=sharing`

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and targets or limits on these metric values might apply to subsets in magnitude, color, or redshift:

- plots of z_{true} *vs.* z_{phot} for visual inspection

- standard deviation and bias in $\Delta z = (z_{\mathrm{true}} - z_{\mathrm{phot}})/(1 + z_{\mathrm{true}})$

- fraction of (catastrophic) outliers, e.g., $\Delta z > 3\sigma$ or $> 0.06 \ (> 1)$

- quantile-quantile (q-q) plots evaluate the shape of $P(z)$

- probability integrated transform, $PIT(z_{\mathrm{phot}}) = \int_0^{z_{\mathrm{phot}}} P(z)\,dz$, calculated for all test galaxies, should be flat for well-estimated $P(z)$ [15]

- the continuous ranking probability score, CRPS, should be a lower value for better estimated $P(z)$, as described in [15]

- redshift confidence for point estimates, $C(z_{\mathrm{phot}}) = \int_{z_{\mathrm{phot}}-0.03}^{z_{\mathrm{phot}}+0.03} P(z)\,dz$

- loss and risk parameters that characterize the photo-z estimates:
  $L(\Delta z) = 1 - \left(1 + \left(\frac{\Delta z}{\gamma}\right)^2\right)^{-1}$, where γ is a characteristic threshold (e.g., 0.15), and:
  $R(z_{\mathrm{phot}}) = \int P(z)\,L(z_{\mathrm{phot}}, z)\,dz$, as described in Tanaka et al. [20]

- the conditional density estimation (CDE) loss as described in Section 4.2 of Schmidt et al. [18]. (Note that the CDE does not strictly require the true posterior be known.)

Sanity Checks– These are tests that can be done using all LSST `Objects` and do not require a truth catalog.

- the uncertainty in z_{phot} should correlate with photometric error

- the star/galaxy flag parameter should agree with photo-z (stars have $z_{\mathrm{phot}} = 0$)

- evolution of $N(z)$ to higher-z for samples with fainter magnitudes, redder colors

Scientific Applications – The following might not be included in the formal validation process, but represent analyses that the broader scientific community may want to do to inform their use of the LSST photo-z.

- assessing the performance of point estimates in broker photometric classification algorithms

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- evaluating the absolute magnitude distribution of Type Ia supernovae once the distance derived from the photo-z point estimates are applied

- evaluating the distributions of derived physical parameters for galaxies using the $P(z)$

- checking whether high SFR galaxies (and maybe other sensitive populations) have reasonable $P(z)$

- galaxy cluster membership identification

- tomographic bin analysis, as in [6]

B.3   Publications that Evaluate Photo-z Estimator Performance

- Hildebrandt et al. [11] tested 18 different photo-z codes on the same sets of simulated and real data and found no significantly outstanding method.

- Dahlen et al. [7] tested 11 different photo-z codes on the CANDLES data set (U-band through infrared photometry) and also find that no method stands out as the "best", and that most of the photo-z codes underestimate their redshift errors.

- Sánchez et al. [17] used the science verification data (200 square degrees of $grizY$ photometry to a depth of $i_{AB} = 24$ magnitudes) of the Dark Energy Survey (DES) to evaluate several photometric redshift estimators. They found that the Trees for Photo-z code (TPZ; Carrasco Kind & Brunner [2]) provided the most accurate results with the highest redshift resolution, and that template-fitting methods also performed well – especially with priors – but that in general there was no clear "winner."

- Tanaka et al. [20] provides a comparative analysis of several photo-z estimators applied to their data set from the HSC Strategic Program. Their website[4] provides comparative analysis plots for each of them.

- Schmidt et al. [18] statistically compare the posterior probability distribution functions produced by 12 photo-z estimators for a mock data set that is representative of the LSST, identifying some biases and shortfalls in both the produced PDFs and the evaluation methods used to analyze them.

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[4]https://hsc-release.mtk.nao.ac.jp/doc/index.php/photometric-redshifts/

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C   Appendix: Data Products Related to LSST Photo-z

For reference, this section provides a preliminary collection of inputs, outputs, and associated products related to generating and serving LSST photo-z:

- the LSST data products needed as input to photo-z estimators (Appendix C.1)

- the required training and calibration data, LSST or external (Appendix C.2)

- the outputs' format, access methods, and documentation (Appendix C.3)

- options for compression to store the results of multiple estimators (Appendix C.4)

C.1   Inputs to Photo-z Estimators

It is important to ensure that all measured quantities needed by photometric redshift estimators are going to be computed and included in the `Object` table. Aside from the fluxes and/or apparent magnitudes and errors for each Rubin Observatory filter, which will be provided in the `Object` catalog, the color properties in the `Object` table might be used for photo-z. *"Colors of the object in 'standard seeing' (for example, the third quartile expected survey seeing in the i band, ~0.9 arcsec) will be measured. These colors are guaranteed to be seeing-insensitive, suitable for estimation of photometric redshifts"* [LSE-163]. In the `Object` table the relevant elements are:

- `stdColor (float[5])` = *'standard color', color of the object measured in 'standard seeing', suitable for photo-z*

- `stdColorErr (float[5])` = *uncertainty on* `stdColor`

Additionally, measured quantities such as the galaxy size, shape, radial profile, 'clumpiness', or surface brightness; the DCR correction (or residual); or a parameter that represents the clustering density within some radius (e.g., 2 Mpc) might all be useful (e.g., as priors) for photo-z estimators. The effective transmission function (ϕ; Eq. 5 in LPM-17), which will be provided for all `Sources` either in the catalog or as a link, is another useful quantity for photo-z estimators.

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C.2 Training and Calibration Data

Spectroscopic Redshifts – Deep multi-band LSST photometry for spectroscopic fields like COSMOS, and/or WFD-depth LSST photometry that overlaps multiplexed spectroscopic surveys like DESI/4MOST, which is obtained either during commissioning or early in Operations year 1, will likely be necessary to produce photo-z for DR1.

Wide Area Imaging – Some photo-z methods have requirements other than spec-z fields: e.g., Sánchez & Bernstein [16] use clustering information to obtain photo-z and this requires wider, shallower field coverage and not a single deep pointing like a spec-z field would have. This wider area would also serve to reduce cosmic variance in the training set (~100 square degrees would serve to average out the variance).

Data Previews – For the community to participate in the training or calibration of a photo-z estimator prior to a data release, it will probably be necessary to release a small ($\sim 10\%$) but representative "DR preview" in advance of each data release during Operations.

C.3 Output Schema, Access Methods, and Documentation

Output Schema – The format of the photo-z output is one of the minimum attributes that must still be defined (§ 3). The photo-z outputs must provide all the necessary inputs to the validation tests, to be defined in Appendix B.2. The currently proposed `Object` catalog table elements related to photo-z are defined in LSE-163 and provided in § E.4, and summarized here:

- posterior probability distribution function (likelihood over redshift)

- a single point estimate with an uncertainty

- quantities related to the posterior (e.g., mode, mean, skewnewss)

- flags (e.g., potential catastrophic outlier, failure mode, consistent with z=0)

Access Methods – The user experience is one of the proposed selection criteria for the LSST photo-z estimator (§ 4). Some examples of publicly released photo-z catalogs which were prepared with a user experience that might be desirable for the LSST photo-z include the Dark

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Energy Survey's Science Portal to serve photometric redshifts [10] and the Hyper SuprimeCam Subaru Strategic Program [20][5].

If the LSST photo-z are not made available in either the `Objects` table or in a federated or joinable catalog – for example in the case where a community-generated photo-z catalog is replacing the DMS-generated catalog (Appendix A.1) – and are instead made available via, e.g., a "photo-z server" (as in [10]), then at least the `Object` catalog ID of the most recent data release should be a queryable parameter.

If the results of multiple estimators are generated, compressed, and stored in the `Objects` table, then decompression should be straightforward for the user (Appendix C.4).

Documentation – Appropriate types of documentation might include published journal articles, GitHub repositories, websites, or other online documentation resources (e.g., `https://readthedocs.org/`). Whatever the format, the documentation contents should include:

- general description of the estimator

- adaptations made to ingest LSST data (compared to past applications)

- an analysis of the training, calibration, and validation processes

- a full list of all inputs and outputs (i.e., a schema browser)

C.4   Storage and Compression

The stored values related to photo-z are subject to the storage space allotted in the `Objects` table as described in § E.4. Both the posteriors and point estimates from several different photo-z estimators could be compressed and stored in this allotted space. Given the variety of use-cases and the fact that different photo-z estimators produce different results [18], the option to compute, compress, and store estimates from multiple estimators in the 2×95 float might be scientifically desirable.

Efficient $P(z)$ compression algorithms are in development, such as Carrasco Kind & Brunner [3] and Malz et al. [14]. Carrasco Kind & Brunner [3] present an algorithm for sparse representation, for which *"an entire PDF can be stored by using a 4-byte integer per basis function"*

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[5] `https://hsc-release.mtk.nao.ac.jp/doc/index.php/photometric-redshifts/`

and *"only ten to twenty points per galaxy are sufficient to reconstruct both the individual PDFs and the ensemble redshift distribution, $N(z)$, to an accuracy of 99.9% when compared to the one built using the original PDFs computed with a resolution of $\delta z = 0.01$, reducing the required storage of two hundred original values by a factor of ten to twenty."* Malz et al. [14] presents a `Python` package for compressing one-dimensional posterior distribution functions (PDFs), demonstrates its performance on several types of photo-z PDFs, and provides a set of recommendations for best practices which should be consulted when DM is making decisions on the DR photo-z data products.

However, compression (and decompression by users) will require extra computational resources, which should be estimated and considered, and decompression must be fast and easy for users.

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D   Appendix: Example Use-Cases for LSST Photo-z

This section contains an incomplete, non-exhaustive summary of a variety of internal and scientific use-cases for the LSST `Object` catalog photo-z. These use-cases inform the minimum attributes and selection criteria proposed in § 3 and 4.

Some of the following information on use-cases was collected from participants of the LSST Project and Community Workshop's session on Photometric Redshifts on Aug 14 2019[6].

D.1   Internal DMS Use-Cases

DM's galaxy photometry outputs are being developed with the goal of feeding photometric redshift estimators, so the computation of photometric redshifts is likely to be a part of the science validation process for LSST photometry. Unlike stars, color-color and color-magnitude diagrams for galaxies do not have sufficient structure to reveal issues with the photometry. While other photometric validation techniques will also be useful (such as evaluating the width of galaxy cluster red-sequences) they may only apply to *some* galaxies, whereas *all* galaxies have a redshift.

The internal use-case of scientifically validating the galaxy photometry outputs is likely to require a simple photo-z estimator which fits SED templates, since the goal is to evaluate whether the photometric outputs match the colors of real galaxies. Whether such a simple SED-fit photo-z could also serve the scientific use-cases is undetermined, because the photometric validation process is not yet defined or written. The internal use-case described in § E.2 – of needing photo-z in order to assess catalog completeness for low- and high-redshift `Objects` – is also likely to be served by a simple SED-fit photo-z estimate.

As a side note, although the DMS will assign fiducial spectral energy distributions (SEDs) to `Objects` in order to apply sub-band wavelength-dependent photometric calibration and PSF modeling, computing photo-z is not planned to be a part of this process. Furthermore, the SED templates used will likely be simpler (e.g., step-function or slope) than would be needed for deriving photo-z.

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[6]Thanks to Sam Schmidt, Chris Morrison, Sugata Kaviraj, Gautham Narayan, Lauren Corlies, Travis Rector, Tina Peters, Alex Malz, Dara Norman, Stephen Smartt, and other participants from the science community.

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D.2   Scientific Use-Cases

A variety of potential scientific applications for the `Object` photo-z are discussed in turn. These scientific use-cases should be used to inform the minimum attributes and selection criteria proposed in § 3 and 4. A summary of the commonalities between science use-cases for photo-z is provided in § D.2.8.

D.2.1   Dark Energy

Extragalactic astrophysics such as weak lensing, baryon acoustic oscillations, and Type Ia supernova cosmology are all main science drivers for the LSST, and all require catalogs of galaxies with photometric redshifts. The photo-z estimators for precision cosmology will be custom-tailored to these particular science goals, and the photo-z results are subject to es-tablished science requirements for dark energy cosmology [21]. For example, weak lensing and large scale structure require ensemble measurements of $N(z)$ and thus require a full posterior PDF, whereas point-estimate photo-z for individual `Objects` are required for Type Ia supernova host galaxies and the identification of strong lensing candidates and galaxy clus-ter members. The Dark Energy Science Collaboration (DESC) is developing specialized photo-z pipelines for these science goals (which *could* serve to generate photo-z for the `Object` catalog, as discussed in Appendix A.1).

D.2.2   Time Domain

The Transients and Variable Stars Science Collaboration reported that they would use LSST-provided `Object` photo-z to identify and/or characterize extragalactic transient host galaxies. Alert packets provide `Object` IDs for the three nearest stars and three nearest galaxies in the most recent data release. Alert stream brokers intend to query the `Objects` catalog in real time to obtain host photo-z because photometric classification for transient light curves is *significantly* aided by redshift estimates. The `Object` catalog's photo-z will also be used to identify and prioritize the potential host galaxies of gravitational wave events for imaging searches of the optical counterpart.

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D.2.3   Galaxies

The Galaxies Science Collaboration reported that they would use LSST-provided `Object` photo-z, and that their science goals require that photo-z be accurate enough ($< 10\%$) to derive intrinsic galaxy properties like mass and star formation rate (SFR). They also indicated that posteriors delivered as $P(z, M)$ and/or with rest-frame apparent magnitudes would be useful to their science goals. This indicates that the results of a template-fitting photo-z estimator might be more relevant to Galaxies studies than machine-learning estimates (especially if the SED templates are associated with intrinsic galaxy properties like mass, metallicity, or star formation rate). The `Object` photo-z might also be used to assist with star-galaxy separation, to enable population studies, to estimate environmental (clustering) parameters, and/or to choose instrument configurations for spectroscopic follow-up (i.e., the expected location of emission lines).

D.2.4   Active Galactic Nuclei

It is currently unclear how useful the `Object` photo-z will be for the AGN community because there is no special deblending planned for the DMS to produce galaxy photometry which is free of AGN emission. The AGN contribution to the DR CoAdd image stacks, and thus the `Object` catalog photometry, will be an average flux over the LSST survey images. Photometric redshift codes will either have to be able to recognize and deal with AGN contamination, or the photo-z estimates for AGN host galaxies will be impacted. Potential AGN contamination could be identified by identifying `DIAObjects` in the nuclear region, but quantifying and removing that AGN flux from the galaxy photometry and recalculating photo-z remain a user-generated data product.

D.2.5   Clustering

Photometric redshifts would likely be used by individuals studying large scale structure and galaxy clustering – for example, as a way to make an initial selection of cluster members.

D.2.6   Stars, Milky Way, and Local Volume

LSST-provided `Object` photo-z could be used to reject compact extragalactic objects from stellar samples for population studies and/or spectroscopic follow-up campaigns.

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D.2.7   Education and Public Outreach

The question *"how far away is it?"* is common to many EPO initiatives and the `Object` catalog photo-z will be used when preparing information for the public. EPO might also use photo-z for, e.g., generating 3D graphics that visualize large volumes, or educational programs on the Hubble constant. For EPO purposes, high precision is not as important as outlier reduction for photo-z.

D.2.8   Science Use-Cases Summary

Aside from the specialized use-cases related to dark energy cosmology, which will be served by customized photo-z estimators developed within DESC, most other scientific scenarios use the `Object` photo-z as point estimates of distance in order to subset the data and identifying targets of interest for follow-up, and/or infer intrinsic galaxy properties.

D.3   Considerations for Maximizing Early Science

To maximize early science capabilities, estimators that will return the most accurate photo-z as early in the survey as possible could be prioritized. In the first year of LSST, it might be simpler to use a template-fitting photo-z estimator and avoid potential issues related to computation resources and/or the need to train a machine learning model. Additionally, the large spectroscopic training sets needed for ML photo-z estimators are more likely to exist by 2030 than at 2020. However, if a machine learning estimator is applied for LSST DR 1 and 2, it should be a community-accepted estimator with demonstrated success in other surveys, preferably surveys that overlap the LSST volume, as this will facilitate the characterization and validation of the LSST photo-z.

E   Appendix: LSST Documentation Review

This section contains a review of all appearances of the terms "photometric redshift", "redshift", or "photo-z" in the LSST documentation. The purpose of this review is to clarify the scope and expected deliverable quality of the Object catalog photo-z, and any internal use-cases (as discussed in further detail in Appendix D.1).

E.1   Science Requirements Document

One of the main science drivers of the LSST design is a significant advance in constraining the models of dark energy cosmology. Section 2.1 of LPM-17 describes the statistical accuracy of photo-z estimates for $i < 25$, $0.3 < z_{\mathrm{phot}} < 3.0$ galaxies which are required for the cosmological probes: root-mean-square error $< 0.02(1 + z_{\mathrm{phot}})$, bias < 0.003, and fraction of catastrophic outliers $< 10\%$. The SRD specifies that these target statistical values *"are the primary drivers for the photometric depth of the main LSST survey."* In other words, the LSST 10-year photometry must enable a state-of-the-art photometric redshift estimator to achieve these targets – they do not apply to the general-use Object catalog photo-z which are the topic of this document.

E.2   Observatory System Specifications

There is a requirement that *"the object catalog completeness"* shall be determined by the DMS   _{OSS-REQ-0164} for *"a variety of astrophysical objects"*, which includes *"small galaxies on both the red- and blue-sequence at a range of redshifts, and supernovae at a range of redshifts"* [LSE-30]. For the DMS to meet this requirement and determine the object catalog completeness for these classes of objects, it requires redshift estimates for Objects. Although spectroscopic redshifts could be obtained and used for this purpose, that would require observing time with non-LSST facilities, and it is instead more feasible that photometric redshifts would be used to meet this requirement.

E.3   Data Management System Requirements

There is a requirement on the Data Management System (DMS) which states that *"The DMS*   _{DMS-REQ-0046} *shall compute a photometric redshift for all detected Objects"* [LSE-61].

No discussion or details are provided regarding how or when the Object photo-z are to be

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calculated, validated, or served, or whether it might be equivalent to serve photo-z computed by a third party (i.e., to federate a user-generated photo-z catalog). It is the current role of this document to evaluate the options for fulfilling this requirement and initiate an LSST Change Request to clarify the computation of `Object` photo-z.

E.4 Data Products Definitions Document

The LSST Data Products Definitions Document (DPDD) [LSE-163] defines the format of the `Object` catalog's table columns which could store the results of photometric redshift estimates, regardless of how they're generated. The following is from Table 5 of the DPDD:

- `photoZ (float[2x95])` = photometric redshift likelihood samples – pairs of redshift and likelihood ($z, \log L$) – computed using a to-be-determined published and widely accepted estimator at the time of LSST Commissioning

- `photoZ_pest (float[10])` = point estimates for the photometric redshift provided in `photoZ`

The exact point estimate quantities stored in the `photoZ_pest` are to-be-determined, *"but likely candidates are the mode, mean, standard deviation, skewness, kurtosis, and 1%, 5%, 25%, 50%, 75%, and 99% points from cumulative distribution"* [LSE-163].

E.5 Data Management Science Pipelines Design

This document clarifies that the photo-z estimator would not be developed by LSST DM, but that DM would be responsible for implementing the code to run on the entire `Objects` catalog and validating the results:

"In addition to data products produced by DM, a data release production also includes official products (essentially additional Object table columns) produced by the community. These include photometric redshifts and dust reddening maps. While DM's mandate does not extend to developing algorithms or code for these quantities, its responsibilities may include validation and running user code at scale" [LDM-151].